

CAN WE **BREAK** THE ADDICTION TO FOSSIL ENERGY?

Proceedings of the 7th Biennial International
Workshop Advances in Energy Studies

Barcelona, Spain, 19-21 October 2010



Editors: Jesús Ramos-Martín, Mario Giampietro,
Sergio Ulgiati, Sandra G.F. Bukkens.

CAN WE BREAK THE ADDICTION TO FOSSIL ENERGY?

**Proceedings of the 7th Biennial International
Workshop Advances in Energy Studies**

Barcelona, Spain 19-21 October 2010

CAN WE BREAK THE ADDICTION TO FOSSIL ENERGY?

**Proceedings of the 7th Biennial International
Workshop Advances in Energy Studies**

Barcelona, Spain 19-21 October 2010

Editors:

Jesús Ramos-Martín

Mario Giampietro

Sergio Ulgiati

Sandra G. F. Bukkens

Sponsored by

Obra Social "la Caixa"

Norwegian Ministry of Petroleum and Energy

Universitat Autònoma de Barcelona

LIPHE4 Scientific Association

Generalitat de Catalunya

Edited by:

Universitat Autònoma de Barcelona

Institute of Environmental Science and Technology

Cover design by:

Emilio Vanni

<http://www.emiliovanni.com/>

Layout by:

Talía Waldrón

ISBN 978-84-938852-9-8

Dipòsit legal: B. 41724-2011

Printed by Reprodisseny

1st edition, 2011

QUOTATION

Since the tenets of our exponential-growth culture (such as a nonzero interest rate) are incompatible with a state of nongrowth, it is understandable that extraordinary efforts will be made to avoid a cessation of growth. Inexorable, however, physical and biological constraints must eventually prevail and appropriate cultural adjustments will have to be made.

Marion King Hubbert

National Energy Conservation Policy Act of 1974, Hearings before the Subcommittee on the Environment of the committee on Interior and Insular Affairs House of Representatives. June 6, 1974.

Social Importance of Energetics

In the author's opinion, at least, this new development promises to be of far more ultimate and permanent importance to the science of human welfare than the earlier incursion of biology in the last century which led to the doctrine of evolution.

Fredrick Soddy

The Role of Money: What It Should Be, Contrasted with What It Has Become.
Routledge: London. p. 5, 1934 [2003]

Workshop Secretariat

Sandra G. F. Bukkens

Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)

Local Organizing Committee

Mario Giampietro

Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)
ICREA Research Professor

Jesús Ramos-Martín

Departament d'Economia i d'Història Econòmica, and
Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)

Katharine N. Farrell

Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)

Tarik Serrano Tovar

Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)

Alevgul Sorman

Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)

International Organizing Committee

Mario Giampietro

Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)
ICREA Research Professor

Sergio Ulgiati

Founder of the Advances in Energy Studies Workshop Series
Department of Sciences for the Environment
Parthenope University of Naples, Italy

Mark T. Brown

Center for Environmental Policy
Department of Environmental Engineering Sciences
University of Florida at Gainesville, USA

Robert A. Herendeen

Gund Institute for Ecological Economics
University of Vermont at Burlington, USA

Kozo Mayumi

Faculty of Integrated Arts and Sciences
The University of Tokushima, Japan

Enrique Ortega

Departamento de Engenharia de Alimentos
FEA-Unicamp, Campinas, Brasil

Hans Schnitzer

Institute for Chemical Engineering Fundamentals and Process Engineering
Graz University of Technology, Austria

PREFACE

From 1998 onwards, every other two years, the Biennial International Workshop “Advances in Energy Studies” (BIWAES) gathers experts in what can be called *energy analysis* to present and discuss advances, innovations and visions in energy and energy-related environmental and socioeconomic issues and models. Renowned energy experts and ecologists, such as H.T. Odum, James Kay, Charles Hall, Tim Allen, Vaclav Smil, Robert Herendeen, Jan Szargut, Joseph Tainter and Robert Ulanowicz among others, have discussed at the BIWAES the importance of energy in our society and ecosystems and the ways to better analyze and model their complex relationships. Previous editions of BIWAES have focused on energy flows in ecology and economy; analysis of the supply side; the ecological consequences of energy sources exploitation; and the role of renewable energy sources and new energy carriers. The present Book of Proceedings refers to the seventh Edition, which took place in the month of October 2010 in Barcelona and addressed society’s addiction to fossil energy.

After the oil price spike of July 2008 and the following global financial crisis, fossil energy re-emerged as a hot topic, not only for theoretical research, but also and mainly for its huge policy implications. The Workshop explicitly addressed the complexity of this issue by focusing on three main topics: i) analysis of the metabolic pattern of societies, ii) analysis of the viability of alternative energy sources, and iii) scenarios of energy transition away from fossil energy.

What came out of the Workshop was a shared concern about the lack of effective conceptual frameworks to address the energy problems associated with the new “energy reality” faced in the third millennium. Humankind will have to learn how to adapt and change quite quickly in times of tough competition for fossil energy sources, economic turndown, and increasing environmental problems. But let’s assume for a moment that the miraculous discovery of a “silver bullet” capable of producing an unlimited supply of energy at very low cost will make it possible to run the economy without any significant downsizing. Still, a business-as-usual economy capable of pursuing the goal of perpetual growth will keep increasing the number of cars, the amount of land covered by roads and parking lots, the extraction of minerals for industrial activities, the amount of sediments moved to the oceans by agricultural production as well as the material moved around because of construction and industrial sectors, the use of water (already facing a situation of “peak water”), and the pressure on disappearing forests and ocean ecosystems already in critical conditions. Sustainability simply cannot be tackled by addressing a single issue at the time! From the discussions held during the Workshop it clearly emerged that energy (peak oil) and climate change are just two symptoms of a more profound global crisis. When dealing with phenomena associated with complex dynamics it is necessary to adopt holistic visions, complex evaluation procedures, and flexible policy tools.

As a matter of fact, newspapers and TV screens are increasingly occupied by news referring to environmental, economic, and energy crises in a continuous rotation. This is a clear sign of a systemic crisis of the business-as-usual model of economic growth that has reached the sustainability limits. There is nothing intrinsically bad with economic growth; it worked pretty well for those that managed to improve their material standard of living without excessive environmental degradation or social injustice. The problem of

perpetual economic growth resides with the finite scale of our planet and with the fragility of social fabric that cannot be stressed too much by sudden changes. Unlimited economic growth is simply impossible on a limited planet and a forced total “westernization” of the entire world population toward a common pattern of production and consumption of a common set of goods and services is certainly undesirable. Sustainability requires cultural diversity and a diversity of metabolic patterns. The sooner modern society will reflect on this point the sooner it will become possible to discuss alternative paths of development.

As surprising as it may be, we do not have a word to specifically refer to qualitative progress that is not associated with growth. As a consequence, proposed terms, such as de-growth, way-down or down-sizing, always bear a “negative” meaning. A sustainability revolution should start with a semantic shift towards the awareness that the words we use are not neutral. They have a built-in judgment of value according to the dominating paradigm. For this reason, our effort should be aimed not only at finding better analytical tools for studying our sustainability predicament, but also at establishing a new sustainability discourse in our society. Put it another way, we need a new approach to control the quality of the process used to produce and consume scientific knowledge in decision-making (on the technical side), and an expansion of the perceptions, epistemologies and languages used to frame sustainability issues (on the cultural side).

As Editors, we did not alter or constrain the content of any paper, and responsibility thus entirely lies with the respective Authors. Interested readers are encouraged to directly contact the corresponding Authors (a list of Workshop participants is included in the last pages).

As Organizers of the Workshop, we would like to acknowledge the help and assistance received from the Members of the Scientific Committee, from several Colleagues from all over the world, as well as from the local organizing team (including students and administration), and, of course, the various sponsors that endorsed the event. We look forward to the continuation of this successful critical dialogue among scientists and society in the next Workshop editions.

Jesús Ramos-Martín^{1,2}, Mario Giampietro^{2,3}, Sergio Ulgiati⁴, and Sandra G. F. Bukkens²

1. Departament d'Economia i d'Història Econòmica, Universitat Autònoma de Barcelona (UAB)
2. Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona (UAB)
3. ICREA Research Professor
4. Department of Sciences for the Environment, Parthenope University of Naples, Italy

INDEX OF CONTENTS

PLENARY SESSION

Hall C. A. S.

ADJUSTING TO NEW ENERGY REALITIES IN THE SECOND HALF OF THE
AGE OF OIL 3

SESSION 1.1

UNDERSTANDING THE SITUATION: ANALYSIS OF THE METABOLIC
PATTERNS OF SOCIETIES

Brown M. T. and Ulgiati S.

PUTTING METABOLIC PATTERNS OF SOCIETY WITHIN A LARGER
PERSPECTIVE 7

Sorman A. H. and Giampietro M.

ANALYSING METABOLIC TRENDS OF EUROPEAN COUNTRIES TO COME
TO TERMS WITH ENERGETIC REALITIES..... 17

SESSION 1.2

URBAN METABOLIC PATTERNS

Hall M. H.

POSITIONING RUST BELT CITIES FOR A SUSTAINABLE FUTURE: STEP 1,
AN EVALUATION OF NEIGHBORHOOD SOCIO-ECOLOGICAL
METABOLISM..... 29

Fath B. D., Zhang Y., Yang Z., Li S.

URBAN ENERGY METABOLISM USING ECOLOGICAL NETWORK
ANALYSIS: CASE STUDY OF FOUR CHINESE CITIES 31

Basireddy, S. R. and Nathan, H. S. K.

ENERGY INFRASTRUCTURE FOR A HIGH HUMANE AND LOW CARBON
FUTURE..... 39

SESSION 1.3

MODELLING CHANGES IN THE METABOLISM OF SOCIETIES

Schramski J. R., Rutz Z. J., Gattie D. K., Li K.

MODELLING A TROPHICALLY BALANCED ECONOMY 51

Némoz S.

THE MEANING OF REBOUND EFFECTS IN THE ENERGY-RELATED PRACTICES OF HOUSEHOLDS..... 61

Iorgulescu R. I., Albu L. L., Stanica C., Polimeni J. M.

ROMANIAN METABOLISM AND SUSTAINABLE POLICIES (MUSIASSEM AT LEVEL N-4) 71

Karakatsanis G.

MODELLING THE ENERGY DYNAMICS OF HUMAN CIVILIZATIONS WITHIN THE THEORY OF CULTURAL EVOLUTIONISM 81

Luzzati T. and Orsini M.

A ROBUSTNESS EXERCISE ON THE EKC FOR CO₂ EMISSIONS 91

Dogaru V.

PROPOSAL FOR AN ANALYTICAL SIMILE FOR INTRA-EUROPEAN EXCHANGE OF MATTER-ENERGY. MANOILESCU – GEORGESCU-ROEGEN MODEL 99

SESSION 1.4

ENERGY METABOLISM AND THE ENVIRONMENT

Bardi U., Lavacchi A., and Yaxley L.

EROEI AND NET ENERGY IN THE EXPLOITATION OF NATURAL RESOURCES. A STUDY BASED ON THE LOTKA-VOLTERRA MODEL..... 111

Cherubini F., Peters G. P., Berntsen T., Strømman A. H., Hertwich E.

BIOENERGY AND ITS ACTUAL MITIGATION OF CLIMATE CHANGE: DOES CARBON NEUTRAL MEAN CLIMATE NEUTRAL? 119

Martínez A., Uche J., Carrasquer B., Rubio C.

SEARCHING MEANINGFUL INDICATORS WITHIN THE WATER WORLD. HOW CAN EXERGY HELP?..... 129

Bukowski M., Manteuffel Szoeg H.

ENVIRONMENTAL IMPACT OF USING DIFFERENT ENERGY SOURCES FOR FAMILY HOUSE HEATING 139

SESSION 2.1

EVALUATING ALTERNATIVES TO FOSSIL ENERGY

Dittmar M.

NUCLEAR ENERGY: STATUS AND FUTURE LIMITATIONS..... 149

Nonhebel S.

ON THE COMPETITION BETWEEN FOOD, FEED AND FUEL..... 159

Li X., Hubacek K., Siu Y. L.

WIND POWER IN CHINA: DREAM OR REALITY 169

Raugei M., Fthenakis V., Fullana-i-Palmer P.

DISPELLING THE MISCONCEPTION OF LOW-EROI PHOTOVOLTAICS:
PEAK OIL IS HERE, LET US NOT SQUANDER WHAT IS LEFT..... 179

SESSION 2.2

CHALLENGES OF FUTURE ELECTRICITY SUPPLY

Müller J., Rommel J.

IS THERE A FUTURE ROLE FOR URBAN ELECTRICITY COOPERATIVES?
THE CASE OF GREENPEACE ENERGY..... 185

Ghisellini P., Rota C., and Ulgiati S.

ENVIRONMENTAL, ECONOMIC AND FINANCIAL UNCERTAINTIES OF
NUCLEAR ELECTRICITY 197

Gabarrell X., Amat E., Oliver Solà J., Gasol C. M., & Rieradevall J.

THE EFFECTS OF USING DIFFERENT MIXES OF ENERGY SOURCES IN
THE GENERATION OF ELECTRICITY IN EUROPE..... 209

SESSION 2.3

INTEGRATING ENERGY SYSTEMS WITH NATURAL PROCESSES

Gaudreau K., Gibson R. B., Fraser R. A.

INTEGRATED SUSTAINABILITY AND SYSTEMS ASSESSMENT APPLIED
TO SMALL-SCALE BIODIESEL IN BARBADOS 221

Agostinho F. and Ortega E.

INTEGRATED FOOD, ENERGY AND ENVIRONMENTAL SERVICES
PRODUCTION AS AN ALTERNATIVE FOR SMALL RURAL PROPERTIES IN
BRAZIL..... 231

Siciliano G.

THE SOCIO-ECONOMIC AND BIOPHYSICAL DIMENSIONS OF
URBANIZATION STRATEGIES IN RURAL CHINA: LAND USE CHANGES,
HUMAN TIME AND ENERGY INTENSITY 245

Buonocore E., Franzese P. P., Ulgiati S.

ALTERNATIVE ENERGY SOURCES: INTEGRATING URBAN WASTEWATER
TREATMENT AND WOOD BIOMASS PRODUCTION FOR BIOENERGY
PURPOSE..... 257

Carrasquer B., Martínez A. and Uche J.

AN ANALYSIS OF TECHNICAL ALTERNATIVES IN A WASTEWATER
TREATMENT PLANT BY USING SLUDGE AS ENERGY RESOURCE 267

Foran B.

LOW CARBON TRANSITION OPTIONS FOR AUSTRALIA..... 277

SESSION 3.1

SCENARIOS OF ENERGY TRANSITION AWAY FROM FOSSIL
ENERGY

Schnitzer H.

NATURAL GROWTH CURVES FOR MODELLING THE TRANSITION TO A
POST CARBON SOCIETY..... 289

Opstelten I. J., Weterings R., Versteeg F. A.

ENERGY TRANSITION OF A SECTOR IN THE NETHERLANDS 299

Matutinović I.

INSTITUTIONS FOR ENERGY TRANSITION AT THE PEAK OF THE OIL AGE
..... 309

Krómer I.

PROSPECTIVE LIFE-CYCLE UNCERTAINTIES OF EMERGING ENERGY
TECHNOLOGIES..... 319

Sousa C. & Cabugueira M.

OPTIMIZATION PROPOSAL OF THE RES-E SUPPORT MODEL IN
PORTUGAL: COMPARISON OF THE PORTUGUESE, SPANISH AND
GERMAN MODELS 327

SESSION 3.2

CREATING BETTER ENERGY STATISTICS FOR GENERATING MORE
ROBUST ENERGY SCENARIO

Giampietro M. and Sorman A. H.

ARE ENERGY STATISTICS USEFUL FOR MAKING ENERGY SCENARIOS?
..... 337

Bøeng A. C.

THE MAKER'S PERSPECTIVE ON ENERGY STATISTICS 351

Vetrella G., Femia A.

FROM BALANCES TO ACCOUNTS: A MEANINGFUL REORGANISATION OF
ENERGY DATA..... 361

CONCLUDING SESSION

WHERE DO WE GO FROM HERE?

Tverberg G. E.

PEAK OIL AND THE CONTINUING FINANCIAL CRISIS 371

POSTERS

ANALYSIS OF TECHNOLOGICAL SOLUTIONS

Suomalainen K., Juliano M., Silva C., Connors S., Ferrão P.

WIND SPEED DYNAMICS IN COASTAL AREAS VS. MOUNTAIN RANGES –
IMPLICATIONS OF DIURNAL VARIABILITY IN URBAN WIND POWER..... 385

Bravi M., Parisi M. L., Tiezzi E. and Basosi R.

LIFE CYCLE ASSESSMENT OF ADVANCED TECHNOLOGIES FOR
PHOTOVOLTAIC PANELS PRODUCTION 393

Carrasquer B., Uche J. and Martínez A.

CALCULATING THE EFFICIENCY OF CURRENT HYDROPOWER
TECHNOLOGY IN THE SEGRE-NOGUERA PALLARESA BASIN FROM THE
EXERGY APPROACH..... 395

Círez F., Bayod A. A., Uche J., Martínez A.

WATER SUPPLY IN THE CIRCE ZERO EMISSION BUILDING: RELIABLE
ED+PV SYSTEM SIZING 405

Cetin E., Yilanci A., Ozturk H. K., Hekim M., Kasikci I., Colak M., Icli S.

SIMULATION AND APPLICATION OF A DC ENERGY DISTRIBUTION
SYSTEM FOR HYBRID RENEWABLE ENERGY SYSTEMS 415

Uçkan G., Öztürk H. K., İçli S.

MATHEMATICAL MODELING AND SIMULATION OF HYBRID PARABOLIC
SYSTEM IN KIZILDERE DENZLI TURKEY 425

Bertrand A., Koster D.

DETAILED ENERGY CONSUMPTION ASSESSMENT OF DIFFERENT
SUPERMARKET REFRIGERATION CONFIGURATIONS IN LUXEMBOURG
..... 433

Kawakami M. and Yamanaka K.

SPECIAL PAINT APPLICATIONS FOR ENERGE SAVING AND CO₂
EMISSION REDUNTION IN WINTER..... 441

Ishimatsu K., Leach M., Ito K., Mitani Y.

GREEN ROOFS FOR URBAN AREAS: EFFECT OF IRRIGATED-SOIL
COVERED ROOFS FOR COOLING 447

Kvesitadze G., Sadunishvili T., Dudaauri T., Metreveli B., Jobava M.

TWO-STAGE ANAEROBIC PROCESS FOR BIO-HYDROGEN AND BIO-
METHANE COMBINED PRODUCTION FROM BIODEGRADABLE SOLID
WASTES 457

Benini L., Torri C., Bandini V., Marazza D., Marotta L., Contin A.

AGRICULTURAL RESIDUES FOR ENERGY PRODUCTION AND CARBON
STORAGE INTO SOILS: A WIN – WIN OPTION? 463

INTEGRATED ANALYSIS OF SUSTAINABILITY

Zucaro A., Buchan K., Mellino S., Viglia S. and Ulgiati S.

ENERGY AND ENVIRONMENTAL PERFORMANCE OF NATIONAL
AGRICULTURAL SECTORS. ITALIAN AND SCOTTISH CASE STUDIES ... 473

Fahd S., Fiorentino G., Mellino S., Rótolo G. and Ulgiati S.

ENERGY, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF NON-
FOOD USE OF *BRASSICA CARINATA* 485

Markussen M. V. and Østergård H.

VIABILITY OF BIOFUELS AS INFLUENCED BY AGRICULTURAL
PRODUCTION SYSTEM..... 495

Cavalett O., D'Angelo S., Franzese P. P.

ENERGY AND EMERGY EVALUATIONS OF AGRICULTURAL AND
FARMING PRODUCTION SYSTEMS IN THE TOLEDO RIVER BASIN
(BRAZIL) 497

Bright R. M., Strømman A. H., Peters G. P.

RADIATIVE FORCING IMPACTS OF BOREAL FOREST BIOFUELS: A
DYNAMIC STUDY FOR NORWAY IN LIGHT OF ALBEDO..... 505

Marotta L., Benini L., Vogli L., Bandini V., Deandrea G., and Marazza D.	
INDICATORS, EMERGETIC THRESHOLDS AND CONSTRAINTS FOR COASTAL SPATIAL PLANNING AND MANAGEMENT	507
Bayod-Rújula A. A., Martínez A.	
DEFOSSILIZATION: LINKING ENERGY CONSUMPTION AND RENEWABLE GENERATION.....	517
Philomena A. L.	
HYDROELECTRICITY AS ALTERNATIVE IS A REAL CLEAN ENERGY? THE BELO MONTE CASE	527
Andersen Chinbuah A.	
INTERNATIONAL COMPARISON OF THE EXOSOMATIC ENERGY METABOLIC PROFILE OF DEVELOPED ECONOMIES.....	529
Marques A., Rodrigues J. and Domingos T.	
THE CIRCULAR FLOW OF CO ₂ EMISSIONS EMBODIED IN INTERNATIONAL TRADE	541
Pasquini A., Tedeschi A.	
SOCIETY PERCEPTION OF ENVIRONMENTAL RISKS	543
 DISCUSSION OF SCENARIOS	
Häyhä T., Franzese P. P., Ulgiati S.	
REDUCING THE USE OF FOSSIL FUELS: SCENARIOS FOR FINLAND'S ENERGY FUTURE.....	553
Krizek K. J. and Marshall J.	
MEASURING AND ANALYZING THE SUBSTITUTION EFFECTS OF NON- AUTO TRAVEL AND IMPLICATIONS FOR FOSSIL ENERGY USE: ISSUES, PRESCRIPTIONS, AND EXAMPLES	563
Jablonska B., Ruijg G. J., Opstelten I. J., Willems E., Epema T.	
TRANSITION TO SUSTAINABLE ENERGY NEUTRAL DISTRICTS BEFORE 2050: INNOVATIVE CONCEPTS AND PILOTS FOR THE BUILT ENVIRONMENT	565
Sagebiel J., Rommel K., Rommel J.	
HOW MUCH ARE CONSUMERS WILLING TO PAY FOR IMPROVED AND GREENER ELECTRICITY SUPPLY? RESULTS FROM CHOICE EXPERIMENTS IN HYDERABAD, INDIA	575

Benes I. and Benesova Z.

CZECH PUBLICS' ATTITUDE TOWARDS ENERGY ISSUES AND TOWARDS THE DESERTEC PROJECT 577

Diaz Maurin F.

TENTATIVE IDEAS TO EXPLORE THE VIABILITY OF THE NUCLEAR OPTION 579

Johansson S., Liljequist K., Ohlander L., Aleklett K.

CAN AGRICULTURE PROVIDE US WITH BOTH FOOD AND FUEL? 591

Viglia S., Gravitis J., Mellino S., Ortega E., Monteiro Souza A. and Ulgiati S.

HOW AND HOW MUCH CAN FOREST ECOSYSTEMS SUPPORT THE PROSPEROUS WAY DOWN? 595

Cabrera Serrenho A., Sousa T., and Domingos T.

GROWTH MODELS: THE ROLE OF ENERGY 597

Rathmann R., Szklo A. and Schaeffer R.

MITIGATION POLICIES IN NON-ANNEX I COUNTRIES: IMPACTS ON COMPETITIVENESS OF BRAZILIAN ENERGY-INTENSIVE INDUSTRIES . 599

Ortega E., Ferraz J. M. G., Comar M. V., Odum E. C.

BUILDING UP A PROSPEROUS WAY DOWN IN BRAZIL 611

METHODOLOGIES: THEORY AND APPLICATIONS

Recalde M. and Ramos-Martín J.

ON WHY ARGENTINA IS INCREASING ITS ENERGY INTENSITY: A MULTI-SCALE INTEGRATED ANALYSIS OF ITS ENERGY METABOLISM 625

Ariza-Montobbio P. and Sorman A. H.

THE RURAL-URBAN ENERGY METABOLISM OF CATALUNYA 635

Scacchi C., Tiruta-Barna L., Benetto E., Loubet P., Jury C., Baudin I.

ASSESSMENT OF DIRECT, INDIRECT AND ECOLOGICAL EXERGY CONSUMPTIONS OF DRINKING WATER PRODUCTION. HOW DOES THE EVALUATION PERSPECTIVE AFFECT THE ENVIRONMENTAL ASSESSMENT? 637

Paleta R.

MULTI-OBJECTIVE OPTIMIZATION FOR REMOTE AUTONOMOUS ENERGY SYSTEMS 645

Wächter P., Ornetzeder M., Schreuer A.	
CRITICAL ISSUES IN THE SPATIAL ORGANISATION IN THE TRANSITION TO A SUSTAINABLE ENERGY SYSTEM.....	647
Ruzzenenti F., Garlaschelli D. and Basosi R.	
ON <i>BENEFITS</i> AND <i>PERSPECTIVES</i> OF APPLYING NETWORK THEORY TO ENERGY SYSTEMS	655
Freire González J.	
THE EFFECTS OF ENERGY-SAVING TECHNOLOGICAL CHANGE ON ENERGY CONSUMPTION: ASSESSING THE REBOUND EFFECT	667
Levin A.	
COMMUNICATING EMERGY ANALYSIS AS FOOTPRINT AND EMERGY PROFILE	677
Pereira L., Zucaro A., Ortega E. and Ulgiati S.	
WEALTH, TRADE AND ENVIRONMENT IN BRAZIL AND ITALY. AN EMERGY-BASED COMPARISON OF CARRYING CAPACITY, ECONOMIC PERFORMANCE AND WELLBEING	685
Nakajima E. S., Gonçalves Pereira L., Ortega E.	
SUSTAINABILITY ASSESSMENT FOR IBIUNA COUNTY, SAO PAULO, BRAZIL THROUGH EMERGY EVALUATION.....	695
Brown M. T., Protano G., and Ulgiati S.	
AN EMERGY ASSESSMENT OF WORLDWIDE BIOGEOCHEMICAL FORMATION OF COAL, OIL AND NATURAL GAS.....	703
Takahashi F. and Ortega E.	
EMERGY EVALUATION OF AVOCADO CROP AS RAW MATERIAL FOR BIODIESEL PRODUCTION	715

PLENARY SESSION

Hall C. A. S.

ADJUSTING TO NEW ENERGY REALITIES IN THE SECOND HALF OF THE
AGE OF OIL

ADJUSTING TO NEW ENERGY REALITIES IN THE SECOND HALF OF THE AGE OF OIL

*Charles A. S. Hall**

State University of New York Syracuse, NY, USA

ABSTRACT

Economic growth, i.e. increasing real GDP, has been used as a panacea for almost all socioeconomic issues that have arisen over the past 40 years. But growing the economy usually requires increasing the throughput of energy, which has been supplied principally by fossil fuels, most importantly oil. The future growth and perhaps even supply of oil globally may be constrained, and some believe that the supply of conventional oil will never increase much beyond today's level, which, at a very minimum, poses a serious problem for "business as usual" economic growth within the U.S.

Our research indicates that real economic growth of 3-5% per year, relied on not only an increasing, but also on an inexpensive, oil supply. To address whether or not business as usual economic growth is possible in the long term, we reviewed the literature on both peak oil and EROI and synthesized a new model indicating how both may impact the future supply and price of oil, and hence economic growth. Our results indicate that: 1) conventional and hence cheap oil supplies cannot increase much beyond current levels for a prolonged period of time. 2) Any expansion in the oil supply must be of lower Energy Return On Investment (EROI). Therefore it will become increasingly difficult to have real economic growth because new, low EROI fields, must produce enough oil to match not only the depletion of the existing field stock but also to overcome the decline in EROI. 3) Decreasing EROI is likely to increase the future price of oil and constrain economic growth.

Peak oil presents society with a new economic paradigm regulated by a system of insidious feedbacks between EROI, oil supply, and oil price. These feedbacks establish an economic growth paradox: maintaining business as usual economic growth will undermine its own success by requiring the production of new sources of oil, but the only sources of oil remaining have a low EROI (i.e. high price), which will undermine further economic growth. From this we conclude that the economic growth of the past 40 years can not possibly continue within the next 40 years unless there is some remarkable, and to us unknown, change in how we undertake our economy.

* E-mail: chall@esf.edu

SESSION 1.1

UNDERSTANDING THE SITUATION: ANALYSIS OF THE METABOLIC PATTERNS OF SOCIETIES

Brown M. T. and Ulgiati S.

PUTTING METABOLIC PATTERNS OF SOCIETY WITHIN A LARGER PERSPECTIVE

Sorman A. H. and Giampietro M.

ANALYSING METABOLIC TRENDS OF EUROPEAN COUNTRIES TO COME TO TERMS WITH ENERGETIC REALITIES

PUTTING METABOLIC PATTERNS OF SOCIETY WITHIN A LARGER PERSPECTIVE

Mark T. Brown¹ and Sergio Ulgiati^{*2}

¹ University of Florida, USA

² Parthenope University of Naples, Italy

ABSTRACT

Suggesting that energy is solely the problem and that what is needed is replacing dwindling supplies of oil with another source is probably counter productive in the short run and may be disastrous in the long run. In earlier papers we have stressed that energy is not the only resource driving economies; equally, and possibly more important, are material resources such as biodiversity, water, topsoil, and minerals as well as the proper accounting methods to value them. The word economy is associated with money in most people's minds. Very rarely is there mention of energy, natural resources, or environment in definitions of economy. Energy and other resources drive the circulation of money and no circulation of money is possible independent of resources. The recent economic meltdown in the USA and in similar economies world-wide has reinforced our understanding of the effects of decoupling monetary growth and resources. Furthermore, concern for peak oil and suggestions that it may have contributed to the global economic woes may have added confusion over the underlying causes and sent a misleading message to the public and to policy makers. Radical changes are necessary for the transition to a more sustainable future with lower availability of resources. This cannot be done without a systemic understanding of the place of humans and their economy within the wider economy of the biosphere.

Keywords: Economic growth, societal metabolism, energy, emergy

1. INTRODUCTION

The G-20 Toronto Summit for International Economic Cooperation, June 2010, resulted in 48 resolutions on international economic cooperation. The second resolution was as follows:

Building on our achievements in addressing the global economic crisis, we have agreed on the next steps we should take to ensure a *full return to growth* with quality jobs, to reform and strengthen financial systems, and to *create strong, sustainable and balanced global growth*. (our emphasis added)

In the 27 pages of resolutions and annexes in support of those resolutions, the term "growth" was used 67 times and the terms "sustain", "sustainable", "sustainability" most often coupled to growth were used 43 times. Even more telling, the terms "resource(s)" while used 17 times never once mentioned natural resources (only referring to financial resources), and the term "energy" was never mentioned at all. Of course we appreciate their effort on behalf of the people of the world as they try to "fix" the world economy. Yet, we are concerned that relying on the same old economic

* Corresponding author; E-mail: sergio.ulgiati@unipartenope.it; Tel: +39 3388053807

rhetoric and stimulus packages will not fix the problems, but could at this juncture create even more problems. Economies rely on resources and services provided for free by the past and present work of the biosphere. Since such resources are not unlimited and since we cannot change the rate at which they are provided, economies are constrained in quantity and time and cannot grow without limit on a limited planet. Acknowledging the nature of these limits, and adjusting our expectations to them is a mandatory prerequisite for sound economic policy.

2. THE EMERGY SYNTHESIS PERSPECTIVE

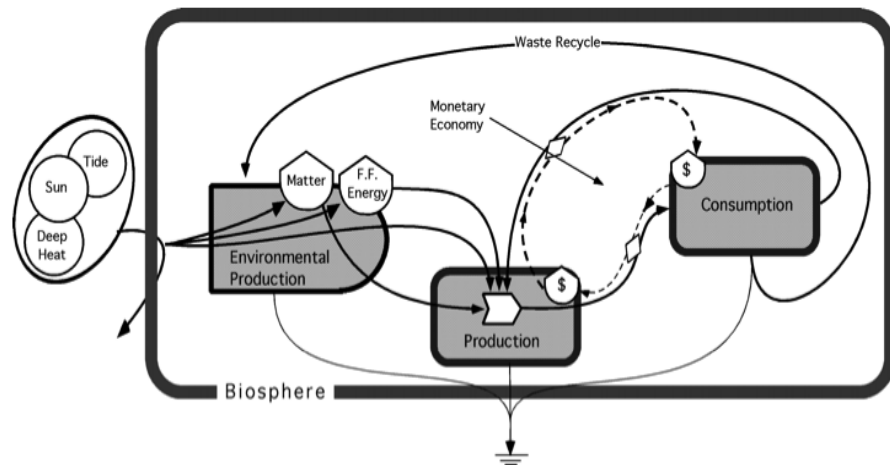
In this paper we provide data in an accounting system, named **emergy synthesis** (Odum, 1988, 1996; Brown and Ulgiati, 2004) that incorporates both the monetary economy and the biophysical economy of the biosphere. Emergy incorporates the environment by accounting for the work done by nature to generate resources (natural capital) and provide ecosystem services. It expresses all resources on a common basis, in solar equivalents (abbreviated seJ, for solar emergy Joules), which makes the work of environmental systems and human systems comparable and analytical insights more comprehensive. It recognizes that the economic system is a subsystem of the larger geobiosphere system that supports and at the same time constrains it by providing flows of energy and material resources that often have no markets and cannot be valued using willingness-to pay.

Since the first papers by HT Odum (1971, 1973, 1986, 1988, among others) using net energy concepts and systems thinking to explore alternatives to neoclassical economics and related monetary accounting systems, the mainstream disciplines of economics and ecology have dismissed it under various critiques that rely on minor deficiencies disregarding the big picture or as Odum used to say, relying on the microscope instead of the macroscope. More important in this pioneering perspective is what Odum often pointed out...the fact that mainstream economics did not recognize nor understand the limitations (and opportunities) imposed by ecological realities on human economies (Odum, 1973). He was not the only one, consider the writings of Shumacher, (1973) and Georgescu-Roegen (1971). What each of these thinkers were, in essence, contributing was not a fix to the existing market theories and monetary accounting methods, but instead a complete overhaul of economic theory that recognized and incorporated biophysical realities (i.e. what is now referred to by some as the "ecological economics" framework). Focusing on ecological constraints and biophysical accounting of resources suggests that unlimited growth on a finite planet, endowed with finite resources is impossible and looking for unlimited growth is the expressway to disaster.

3. THE BIOPHYSICAL ECONOMY

The biophysical economic system is composed of flows of matter, energy, and information with counter-current flows of money as shown in Figure 1. The most striking difference between this depiction of the economy and standard text book diagrams of economic system is the driving energies and the environment that, in general, are completely ignored when one only looks at the economy as a circulation of money and goods and services between producers and consumers. From a *biophysical* point of view, energy and other resources drive the circulation of money and no circulation of money is possible independent of resources. Thus in Figure 1 the monetary economy is shown being driven by *flow-limited* renewable sources and *limited* storages of matter and fossil fuels.

Figure 1. The biophysical economy. Economic production (center) is a function of renewable energy, materials and non-renewable energy from environmental production and an input of labor (information). The monetary economy represents about 86% of the total emergy budget of the Earth.

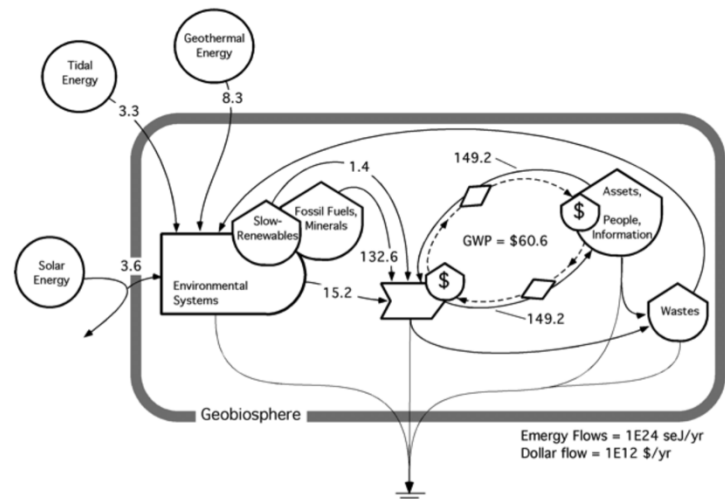


Often called *neoclassical economics*, the theories and concepts that explain the functioning of the monetary economy are concerned with prices and the “allocation of scarce resources among competing ends”. Within the confines of the monetary economy (ie the right hand side of Figure 1) these concepts and theories of how and why it works are accepted by many but also challenged by an increasing number of serious skeptics (see for instance Cleveland, 1991; Dominique, 2001; Hall et al. 2001, Adolphson, 2004; Hall and Klitgaard, 2006; Gowdy, 2007; Nadeau, 2008a,b; and Simms et al., 2010). Neoclassical economics supports the vision that the complexities of the world’s market economies are not subject to thermodynamic limitations; and that the quantity of money can be increased indefinitely through the use of economic instruments with little or no attention to biophysical realities. Yet it is quite evident from present actions of governments throughout the world - who are displacing millions of people, degrading environments, waging wars and creating “economic instruments” for the continued control of countries and their resources - that the entire circulation of money and all the exotic human monetary inventions and ways of making more money, are ultimately driven by the very fundamental energetic principle that work cannot happen without an expenditure of energy. This energy comes in several forms, the non-renewable chemical energy of fuels and other mineral resources and the renewable energies of the geobiosphere.

4. EVALUATING THE BIOPHYSICAL ECONOMY

The biophysical economy is composed of energy flows (quantitative evaluation of resource flows in solar equivalents) that are accompanied by monetary flows. Figure 2 is a simplified diagram showing the total emergy and money circulation in the global biophysical economy in 2008 (Brown and Ulgiati, 1999, updated; 2010). The left side of the diagram shows the environmental systems that provide life support and the biogeologic processes that produce storages of non-renewables and slow-renewables. Currently the renewable environmental portion of the global economy accounts for about 14% ($15.2 \text{ E}24 \text{ seJ/yr}$) of the total emergy budget of the planet, with human released non-renewable resources accounting for about 86% ($110.3 \text{ E}24 \text{ seJ/yr}$). Without continuous inflows of emergy in the form of matter, fossil fuels, and renewable energy, the monetary economy would come to a standstill.

Figure 2. The global economy. The monetary economy (measured by the Gross World Product [GWP]) is driven by the environmental renewable, slow-renewable and non-renewable energy. In 2008, total energy flow supporting the monetary economy was 140.2 E24 seJ/yr and the GWP was \$60.6 trillion.

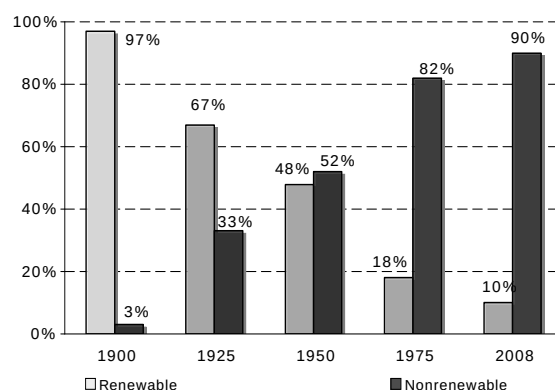


While renewable energy inflow to the planet has remained constant over the years, its share of the total energy driving the geobiosphere has decreased markedly as a percent of the total (Figure 3). In 1900 the renewable energy base of the world's economy was about 97% of the total use. By 1925 the renewable base had decreased to 87% of total use, and in 1950 it had comprised 48% of total use. Since mid century, the energy in non-renewable and slow-renewable sources released by humans has increased so that in 2008 non-renewable energy use equaled 86% of total use and the renewable portion of the global biophysical economy equaled only 14%. Bare in mind, that the biosphere's renewable energy has not shrunk, it has remained constant, the trend shown in Figure 3 is the result of the overwhelming increase in the use of non-renewable energy within the human economy.

The monetary economy has increased in size since the industrial revolution and in the last 50 years has come to dominate the biophysical economy. The graph in Figure 4 shows the change in global energy and Gross World Product (GWP) since 1900. In the early part of the 20th century non-renewable energy released by humans was small compared to the renewable flows of the geobiosphere (the horizontal line representing 15.2 E24 seJ/yr).

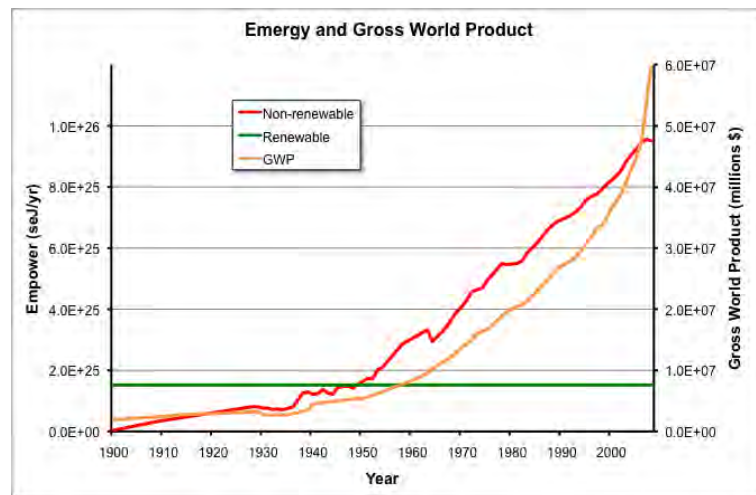
The "great depression" beginning in 1929 slowed the growth of non-renewable consumption for a few years, but World War II quickly made up for the slump. From the end of the war until about 1950 increases in non-renewable use rose at about 1% per year, but beginning in about 1952 until very recently the increase in use averaged about 3.7% per year thus the doubling time was about 19 years. Beginning in 2003 the growth in consumption decreased to about 2% and in 2008, consumption of non-renewables actually decreased by nearly 1% as a result of contraction in the world economy. GWP rose at the same rate as global energy use until the 1950s where it lagged a bit behind energy use. From the mid 1980's until the mid'1990's growth of GWP was roughly the same as increases in energy use, about 3.5%.

Figure 3. The changing percentage of total energy from renewable and non-renewable sources beginning in 1900. While 97% of global production was based on renewable energy flows in 1900, today less than 10% of total energy use is from renewable energy sources.



In the first nine years of the 21st century, however, GWP has increased faster than global energy use, at rates of about 5.6%.³ Since the energy and monetary economies are linked, increases in money supply that are not accompanied by real increases in the supply of energy result in inflation. Thus the difference between the rates of increase of energy use and GWP represent inflation and since energy use was increasing at about 3.7% during 2000-2007 and GWP was increasing at 5.6%, the difference of 1.9% represents inflation.

Figure 4. The growth of global nonrenewable energy use (red line) and Gross World Product (GWP) (gold line) since 1900. The renewable input to the Earth is constant (green line).



The peaking of non-renewable energy use in 2008 and the continued increase in GWP is an important sign of what we believe is driving the current world economic crises and should be cause for serious concern on the part of world leaders. Should non-renewable energy and resource consumption remain leveled or decline and world economic leaders continue to increase money supplies, under the false notion that priming the economic pump will restart global economic growth, the result will be large scale global inflation. It remains to be seen if inputs of non-renewable energy and resources can be increased to match growth expectations of global economies. Overall, the economic policy needed is to match money supplies to resource availability...if resources increase the money supply can be increased, if they decline, the money supply should be decreased. In this way we can avoid the inflation that results when money supplies increase faster than resource inputs and more money chases scarce resources.

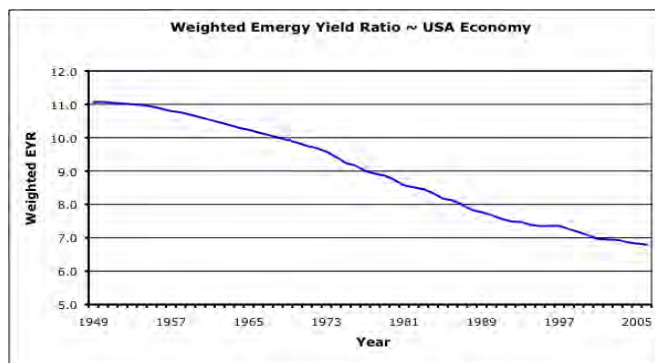
5. NET ENERGY IS IMPORTANT

Resource throughput is central to the welfare of human economies yet this is only true if the effort to get the resources is small compared to the return. The concept of *net energy* (equal to energy of resources delivered by a process minus the energy of resources invested) is central to understanding what can and what cannot be done with resources in relation to human development and sustainability. The ecological concept of "net production" is widely used as a measure of overall development potential in ecological systems. Key to identifying when growth diminishes and eventually stops is when costs of sustaining system processes increases and eventually equals productive processes. The same concepts apply to human dominated systems; when the resource costs of sustaining inflows of new resources (of any kind, not only energy) exceed the return from these new resources, growth stops. Societal infrastructure was built by and its metabolism is driven by a high net yielding resource base that is unlikely to be

³ Aggregating the 144 economies of the world into one world economy hides the fact that some economies were not growing in the first part of the 21st century (much of Europe) while others were actually growing at rates equal to or greater than 10% (India and China). This fact does not deny the validity of our concerns since most of the growth these countries experienced was in support of the high standard of well-being of the west (displaced western growth).

available in the future. A typical case is the oil and minerals that drive our economies. In the past decades their net contributions were large reflecting the fact that they represented millions of years of concentration of biosphere energy. As the easiest and most abundant resources have been exploited, the net yields are declining. Figure 6 shows the decline in the average Energy Yield Ratio [EYR= (emergy exploited + emergy invested)/emergy invested] of the USA energy sources since the mid-1900's.

Figure 6. The change in the combined EYR of energy sources to the USA economy from 1949 to 2006.⁴



As the EYRs from these resources continue to decline, their net emergy yields, i.e. the resources actually exploitable, also decline (consider the costs of the recent BP oil disaster in the Gulf of Mexico and other similar events as further erosion of the net yield of oil) so that growth must slow and stop. Trying to grow the economy when the driving energies are declining will result in inflation equal to or worse than the inflation of the 1970's during and following the oil embargo.

6. THE FALSE PROMISE OF RENEWABLES

While there is much talk of “peak oil” lately, there is little analysis and review of the declining net yields from fossil fuel energy sources that drive our economy. As these limits are felt throughout modern economies, society looks to alternative sources; wind, waves, tides, solar, biomass, bio-ethanol, etc. Renewable energy sources, up to now, have lower net yields than fossil fuels and thus provide false promises to those who are looking for business as usual at the end of cheap oil. It is imperative that the net contributions of proposed new energy sources be evaluated and all costs included. Many of the so-called renewable energy sources are actually consumers of fossil fuels. Take for instance the proposed bioethanol and biodiesel programs, where evaluations over the last decade continue to show net emergy yields of less than 2 to 1 (see for example: Giampietro et al., 1997; Ulgiati, 2001; Rajvanshi, 2010; among others) and confirm similar evaluations of energy return on investment (EROI) (Pimentel and Patzek, 2005; Heinberg, 2009).

The graph in Figure 6 is a weighted average of EYRs of the different energy sources in the USA, but it is confirmed by studies worldwide. Biofuels EYRs typically are less than 2 to 1 (Ulgiati, 2001); silicon photovoltaics EYRs seem only slightly over breakeven, but very few studies are available for a reliable assessment⁵. Other more

⁴ Assumptions to create the graph are as follows: EYR of coal began at 18/1 and declined at a rate of 3.8% per year to end in 2006 at 7.8/1. Natural gas began at 9/1 and declined at a rate of 5.1% per year to end in 2006 at 6.1/1. Petroleum began at 18/1 and declined at a rate of 11% per year ending in 2006 at 7.73/1. Nuclear has remained constant at 4.6/1. Hydroelectric EYR has remained constant at 10/1. Geothermal began in 1960 at 2.66/1 and increased at a rate of 6% per year. Solar PV began around 1990 at 1.0/1 and increased by 3.0% per year up to 1.65/1 in 2006. Wind energy began around 1999 at 8.0/1 and increased at a rate of 8.0% per year, ending in 2006 at 8.6/1. Biomass in 1949 was estimated as 2.0/1 and has increased at a rate of 3.2% per year to end at 3.82/1 in 2006.

⁵ The energy-based EROI of photovoltaics was calculated in the range 3-10 with potential for improvement (Fthenakis et al, 2009; Heinberg, 2009), while EYR seems still slightly below 2. This means that the energy invested is used profitably to convert the solar radiation into electricity, while a low EYR sends a different message. EYR does not deny that more energy can be obtained from PV modules than was invested in technology, but focuses on the global investment of energy and other resources (water, minerals,

traditional renewable energies show higher EYRs, for instance hydropower, geothermal and wind range up to 5 or 6 to 1 in other cases investigated (Brown and Ulgiati, 2002). The problem is that their large-scale implementation is offset by several constraints, the most significant of which is the fact that areas suitable for dams and wind farms are limited. The hydropower industry suggests that the maximum potential hydropower development worldwide will increase total hydroelectricity production only threefold (IHA, 2000). The most optimistic projections for wind electricity suggest it will produce only 6.6% of total electric demand by 2050 (WWEA, 2010).

The International Energy Agency's most optimistic projections for the year 2050 (IEA, 2003; so-called Sustainable Development Vision) foresee a doubling of total energy consumption, of which fossil fuels comprise 54.1%, nuclear 11%, biomass 15.7% and other renewables including hydropower 18.9%. These correspond to growth rates of 480% for nuclear energy, roughly 150% percent increase in biomass use, and 370% growth of other renewables. There is a corresponding 34% decrease in fossil fuel use. The next IEA (2008) baseline scenario confirms the more than double energy consumption, in support of the "expected growth in global economic activity in the next forty years". According to that scenario, not taking action would mean that coal would become the dominating fuel (37% of total primary energy use in 2050) and that the global 2050 CO₂ emissions would reach 62 Gt compared about 14 Gt released in 2005. Oil share would decline from 35% in 2005 to 27%, natural gas from 21% to 20%, nuclear from 6% in 2005 to 4%, and other renewables would decline from 11% to 10%, with hydro remaining constant at 2%. Innovative scenarios (ACT and BLUE) are suggested by IEA, with decreased reliance on fossil fuels (45-59% less than in baseline, although with 34% more natural gas) and increased reliance on nuclear (more than 100% increase, up to about 12% again as in IEA 2003 scenario) and biomass (about 300% more than in 2005) and other renewables (also more than 300% of 2005). IEA (2008) also estimates that the additional investments needed in the energy sector would be about 2005 USD 17 trillion between now and 2050, "...on average around 400 billion per year, roughly equivalent to the gross domestic product (GDP) of the Netherlands, or 0.4% of global GDP each year between now and 2050".

The major question here that begs to be answered is how can these impressive increases in the growth of nuclear, biomass, and renewables be sustained on declining net energy of fossil fuels and the low net yields of the renewables themselves. In addition, there is increasing concern and in some cases, outright rejection by populations regarding nuclear, large hydro-dams, large wind fields and the use of arable and forest land for biofuel production.

Overall, the entire installed power of renewable electric production systems is so small that it is hard to imagine the huge increases that are needed to meet the IEA's Sustainable Development Vision. Put in numbers, the current and projected contributions of wind, tidal, wave, geothermal and biomass energy are as follows:

- 1) Installed wind power is 0.16 TW worldwide translating into a total wind electricity production of 0.03% of world-wide energy consumption (WWEA, 2010)
- 2) Total installed tidal power is 0.3 GW which translates into less than 0.002% of world energy use and the best estimates for future energy production are only 0.2% (a 100 fold increase) of current world energy use (Jones and Finley, 2003).
- 3) McCormick et al. (2009) estimate that a total wave power of .5 TW can be exploited with the existing technology, which, assuming a 37.5% capacity

environmental services, land, labor & information) that are also needed to reach the result. These resources are supplied by society and must be accounted for as further investment costs, diverted from other potential processes. Until breakthrough PV technologies are developed (or better case studies reported), low EYRs do not indicate an important addition of new energy resources to societal uses, but rather a conversion of already available forms of energy into others that are preferred by some users. The society as a whole may not be benefiting much from just supporting one process instead of others. Of course, the same holds for other technologies with low EYR.

factor equals about 1.25% of current world demand for energy. However, at present there are no commercial wave power plants operating worldwide.

4) Present installed geothermal electricity production is 10.7 GW or 0.05% of world energy demand (Bertani, 2003; GEA, 2010;) assuming a capacity factor of 75%. The potential geothermal production has been estimated between 2.3% and 13% of current world demand for energy.

5) Karekezi et al. 2004 estimate that global biomass use in 2001 was 14% of total global energy use. This figure includes traditional fuel wood, electricity from wood and municipal waste combustion, and other miscellaneous uses. Their estimates for the future use of biomass decrease to 11% in 2020 due to increased recycling and increases in total energy uses.

In summary, the false promise of renewables actually has two related parts. The first part is whether there is sufficient net yield from renewables to drive growth or even a steady state economy without fossil fuels. The second is whether there is enough renewable energy on the planet to drive our complex techno-industrial society. We have shown that most renewables have very low net energy yields, that those that have higher yields are limited by the availability of potential sites and the quantity of energy that might be generated, and finally that growth always generates non-negligible environmental impacts. Thus, in reality, the concept of “sustainable growth” on renewable energy sources is a false promise that if pursued, can only add to the economic and environmental catastrophes that are beginning to appear.

7. CONCLUSION: GROWTH IS NOT THE ANSWER

We worry that the dominant economic paradigm, so fixed in the minds of world population, will result in a politics of “growth at any cost” which can easily translate into further escalations of world tensions. The prevailing world-view of many in the west seems to be that the only way to deal with the current global economic and environmental problems is to intensify the patterns of production and consumption that have produced them. Are we destined to blindly follow the path of many post-hunter-gather societies that experienced a period of rapid increase in resource exploitation and population growth followed by an equally rapid economic and ecological collapse (Tainter, 1988; Diamond, 2005; and Turchin, 2005)?

The problem is not just resource availability nor is it finding another energy source. The problem is BUSINESS AS USUAL. The environmental, social, and economic consequences of unlimited cheap energy might be even worse than limited fossil fuels. Our fascination and addiction with continued growth may have unbelievable consequences in the long run. Faced with the possibility of unlimited growth, and its coupled consequences, one can only hope that we fail in our attempts to solve this current crisis so that our focus will turn to living within the planet’s carrying capacity. Some suggest that this will happen, no matter what, and thus the real issue is if we want to be part of the solution or continue to be the problem.

REFERENCES

- Adolphson, D.L. 2004. “A New Perspective on Ethics, Ecology, and Economics”. *Journal of Business Ethics* 54: 203-216, 2004.
- Bertani, R., 2003. “What is geothermal Potential?” Extracted from IGA News, a *Quarterly Newsletter of the International Geothermal Association* No. 53, pages. 1-3, September 2003.
- <http://www.geothermal-energy.org/>;
- http://www.geothermal-energy.org/308,iga_newsletter.html
- Brown, M.T., and Ulgiati, S., 1999. “Emergy evaluation of the biosphere and natural capital”, *Ambio*, 28: 486-493.
- Brown, M.T., and Ulgiati S., 2002. “Emergy evaluations and environmental loading of electricity production systems”. *J Cleaner Prod* 2002; 10(4): 23–36.

- Brown, M.T., and Ulgiati, S., 2004. "Emergy Analysis and Environmental Accounting". In: *Encyclopedia of Energy*, C. Cleveland Editor, Academic Press, Elsevier, Oxford, UK, 2004, pp. 329-354.
- Brown, M.T. and Ulgiati, S., 2010. "Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline". *Ecological Modelling*, 221(20): 2501-2508
- Cleveland, C.J. 1991. "Natural Resource scarcity and economic growth revisited: economic and biophysical perspectives". Pages 289-317 In Costanza, R (ed). *Ecological Economics: the science and management of sustainability*. Columbia University Press, NY
- Daly, H. E. 1991. *Steady-State Economics: Second Edition with New Essays*. Published by Island Press, Washington, DC.
- Diamond J. 2005. *Collapse: How Societies Choose to Fail or Succeed*. New York: Viking Press;
- Fthenakis, V., Kim, H.C., Held, M., Raugei, M., and Krones, J., 2009. "Update of the PV energy payback times and life-cycle greenhouse gas emissions". *Book of Proceedings of the 24th European Photovoltaic Solar Energy Conference, 21-25 September 2009, Hamburg, Germany*. Pp. 4412-4416.
- GEA, 2010. *Geothermal Energy Association Reports*. <http://www.geo-energy.org/reports.aspx>
- Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*. Harvard University Press: Cambridge, Massachusetts.
- Giampietro, M., Ulgiati, S., and Pimentel, D. 1997. "Feasibility of large-scale biofuel production: Does an enlargement of scale change the picture?" *BioScience* 47(9): 587–600.
- Gowdy, J. 2007. "Avoiding self-organized extinction: Toward a co-evolutionary economics of sustainability". *International Journal of Sustainable Development & World Ecology* 14 (2007) 27-36.
- Hall, C. and K. Klitgaard. 2006. "The need for a new, biophysical-based paradigm in economics for the second half of the age of oil". *Journal of Transdisciplinary Research* Vol. 1, Issue 1: 4-22.
- Hall, C.A.S., D. Lindenberger, R. Kummel, T. Kroeger, and W. Eichhorn, 2001. "The Need to Reintegrate the Natural Sciences with Economics". *Bioscience* Vol 51:8, 663-673
- Heinberg, R., 2009. *Searching for A Miracle - Net Energy Limits and the Fate of Industrial Society*. International Forum on Globalization, and the Post Carbon Institute. False Solution Series #4. Pp. 75. Downloadable from <http://www.ifg.org/store.htm#searchingforamiracle>.
- IEA, 2003. *Energy to 2050. Scenarios for a Sustainable Future*. International Energy Agency, Paris. http://www.iea.org/textbase/nppdf/free/2000/2050_2003.pdf.
- IEA, 2008. *Energy Technology Perspectives. Scenarios and Strategies to 2050*. International Energy Agency, Paris. <http://www.iea.org/textbase/nppdf/free/2008/etp2008.pdf>.
- IEA, 2009. *World Energy Outlook 2009. Key World Energy Statistics*. International Energy Agency, Paris. www.iea.org.
- IHA, 2000. *Hydropower and the World's Energy Future. The role of hydropower in bringing clean, renewable, energy to the world*. International Hydropower Association, Compton, West Sussex, United Kingdom; International Commission on Large Dams, Paris, France; Implementing Agreement on Hydropower Technologies and Programmes/International Energy Agency, Paris, France; Canadian Hydropower Association, Ottawa, Ontario, Canada.
- Jones, A.T., and Finley, W., 2003. "Recent Developments in Salinity Gradient Power, Marine Technology Society". *OCEANS 2003*, pp. 2284- 2287; <http://waderllc.com/2284-2287.pdf>
- Karekezi, S., Lata, K., and Coelho, S.T., 2004. "Traditional Biomass Energy. Improving its Use and Moving to Modern Energy Use". Presented at the *International Conference for Renewable Energies, Bonn 2004*. Pp.55. Downloaded from www.renewables2004.de.
- McCormick, Michael E., and R. Cengiz Ertekin. 2009. *Renewable sea power: waves, tides, and thermals--new research funding seeks to put them to work for us*. *Mechanical Engineering-CIME* 131.5 (2009): 36. Expanded Academic ASAP. Web. 5 October 2009. <http://www.allbusiness.com/science-technology/science-funding/12327678-1.html>
- Nadeau, R. 2008a. Brother, "Can You Spare Me a Planet? Mainstream Economics and the Environmental Crisis". *Scientific American*, March 19, 2008.
- Nadeau, R. 2008b. "The Economist Has No Clothes: Unscientific assumptions in economic theory are undermining efforts to solve environmental problems". *Scientific American* March 25, 2008.
- Odum, H.T. 1971. *Environment, Power and Society*. John Wiley, NY.
- Odum, H.T. 1973. "Energy, ecology and economics. Royal Swedish Academy of Science". *AMBIO* 2(6): 220-227.

- Odum, H.T. 1986. *Human ecology*. In McGraw Hill Yearbook of Science and Technology. pp. 236-238.
- Odum H.T., 1988. "Self organization, transformity and information". *Science*, 242: 1132-1139.
- Odum H.T., 1996. *Environmental Accounting. Energy and Environmental Decision Making*. John Wiley & Sons, N.Y. Pp. 370.
- Pimentel, D., Patzek, T.W., 2005. "Ethanol production using corn, switchgrass and wood; biodiesel production using soybean and sunflower". *Natural Resources Research* 14 (1), 65–76.
- Rajvanshi, N. 2010. *Evaluation of assessment methods for bioethanol production*. PhD Dissertation. Department of Mechanical Engineering, University of Florida, Gainesville, FL.
- REN21 (2010). *REN21- Renewable Energy Policy Network for the 21st Century. Renewables 2010 Global Status Report* (<http://www.ren21.net/globalstatusreport/g2010.asp>).
- Schumacher, E.F., 1973. *Small is Beautiful: Economics as if People Mattered*. Harper and Row, New York, 324 pp.
- Simms, A., Johnson, V., and Chowla, P., 2010. *Growth isn't possible. Why we need a new economic direction*. NEF (the new economics foundation), London, & and Schumacher College. Dartington, UK. ISBN 978 190 4882 71 8. Pp. 148
- Tainter J. 1988. *The Collapse of Complex Societies*. London: Cambridge University Press.
- Turchin P. 2005. *Historical Dynamics: Why States Rise and Fall* Princeton NJ: Princeton University Press.
- Ulgiati, S. 2001. "A comprehensive energy and economic assessment of biofuels: when "green" is not enough". *Critical Reviews in Plant Science* 20, 71–106.
- WWEA. 2009. *World Wind Energy Report 2009*. World Wind Energy Association, Bonn, Germany.
http://www.wwindea.org/home/images/stories/worldwindenergyreport2009_s.pdf

ANALYSING METABOLIC TRENDS OF EUROPEAN COUNTRIES TO COME TO TERMS WITH ENERGETIC REALITIES

Alevgul H. Sorman^{*1} and Mario Giampietro²

¹ *Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)*

² *ICREA Research Prof., Institute of Environmental Science and Technology
(ICTA)
Universitat Autònoma de Barcelona (UAB)*

ABSTRACT

Before speculating about our possible roadmaps into a “low carbon economic growth” it would be wise to first understand the nature of the metabolic pattern of modern societies. In particular it would be wise to look into the current breakdown of the total energy consumption across the different sectors of modern societies in order to get an understanding of how energy is produced and consumed across different hierarchical levels. In this article we first propose a different accounting scheme for energetic flows. This scheme clearly distinguishes three different energy forms: Primary Energy Sources (PES), Energy Carriers (EC) and End Uses (EU). Then, using this distinction we trace the different energy flows (per type of energy carrier – heat, fuel and electricity), which are required for the functioning of a modern society in each of its socioeconomic subsectors. By combining this accounting scheme (making a distinction between different energy forms) to a multi-scale integrated assessment (defining different patterns of consumption for different compartments and sub-compartments of society) it becomes possible to study how the emergent properties of the whole (total energy consumption) depends on the characteristics of the parts (expression of an integrated set of functions) and viceversa, how the characteristics of the whole impose constraints on the characteristics of the parts. The metabolism of societies (the flow of energy consumed to reproduce the structures of a society and express their typical functions) can be studied by looking at the metabolic rates [the flow of energy throughput (measured in joules) per hour of human activity (measured in hours) invested in the different compartments] across different levels and subsectors. The resulting profile of energetic metabolic intensities for each sub sector versus the overall profile of energy consumption of a society makes it possible to assess and pinpoint the effect of forced internal relations and critical thresholds. The empirical study presented here shows the trends in the profile of metabolic rates of European Countries in their structural performance over the period of 1990 – 2007. These trends are then commented in relation to their policy implications.

Keywords: Energetic metabolism, Societal metabolism, Energy Accounting, Energy Statistics, Energy Return on Investment (EROI), Primary Energy Sources, Energy Carriers

1. SOCIETAL AND ENERGETIC METABOLISM

The notion of societal metabolism has re-gained momentum in the last decades, principally used as a tool for analyzing society-environment interactions from a biophysical approach which is crucial to bridge to the mainstream readings of economic analyses for describing evolutionary trends of societies (Fischer-Kowalski, 1998; Giampietro, 2000a & 2000b; Martinez-Alier, 1987). Analysing energetic metabolisms of societies puts a special emphasis on studying the dynamic energy budget of societies to account for the requirement and supply of energy flows per hour of human time (divided in working and non-working hours in the society) (Giampietro and Mayumi,

^{*} Corresponding author; E-mail: Alevgul.Sorman@uab.cat; Tel. (+34) 93 586 81 02

2000a, 2000b; Giampietro and Ramos-Martin, 2005). In this way, it becomes possible to observe and analyze changes in the energy throughput within the various sectors of the socioeconomic system with respect to the amount of human time allocated for each sector. Furthermore, focusing on energetic metabolisms of societies not only reveals insights on their current paths of development; but also sheds light on possible future implications on sustainability. For example, looking at the post industrialization phase of Europe, it can be possible to scrutinize the potential implications of the dramatic change in the patterns of production, with a massive switch to a service based economy, obtained by externalizing all energy intensive activities. Yet, unfortunately, until now, the predominant indicator used for assessing energetic performance of economies has been the variable Energy Intensity (Energy Consumed/GDP). Starting with a critical appraisal of this indicator we propose below a different scheme of accounting for assessing energetic flows and their energy intensity. This study specifically focuses on the changes that took place in the metabolic pattern of European Union 14 countries². These changes are represented by considering the mix of energy carriers within the different sectors and the resulting energetic metabolic rates linked to the corresponding economic labour productivity values.

1.1 The misleading Energy Intensity indicator to measure energetic performance

The “Energy Intensity” indicator has been for many years the most commonly used indicator in standard econometric analysis to evaluate energetic performance of modern countries. Yet, in spite of its generalized use, we believe that is not a particularly effective indicator. To illustrate our case, we can consider the energy intensity of El-Salvador (a developing country) and Finland (a developed country) in the year of 1998. Then we find that the value of this indicator is the *same* for these two countries: 12.6 MJ/\$! However, IF the same energy intensity variable is decomposed into the ratio between two metabolic paces; the **GDP/THA (\$/hr)** - the Gross Domestic Product divided by the Total Human Activity (indicating the total amount of hours of human activity associated with a given population) - and **TET/THA (MJ/hr)** (the Total Energy Throughput over the Total Human Activity), THEN it become possible to relate these two benchmark values to “external referents” – i.e. typologies of socio-economic systems such as developed countries or developing countries - that can be compared among each other (See Fig.1). As seen in the figure below, the profiles of a typical developed country (such as Finland) in terms of energy throughput and added value generation are of *one order of magnitude* larger than a typical profile of a developing country (such as El Salvador). Such performance values as are undoubtedly not visualized by the energy intensity indicator alone, thus the use of such an indicator results to be inadequate for characterizing the energetic performance of a given society.

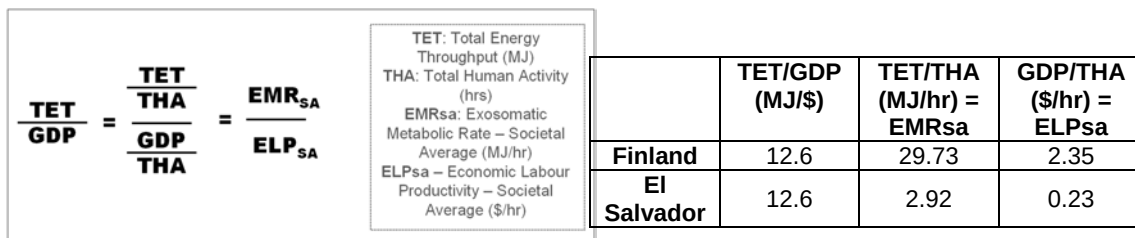


Fig 1. The breakdown of the Energy Intensity Indicator for Finland and El Salvador

² Luxembourg has been omitted from the analysis due to its systemic status of outlier. This status can be explained by a large fraction of its population living outside Luxembourg and yet contributing to the local workforce in Luxembourg.

1.2 Integrated Tools for Analysis and accounting for complex energy flows

Abandoning the idea of using a single indicator approach for evaluating the energetic performance, we can imagine using an integrated set of tools for such an analysis bringing together a set of variables from biophysical to economic domains. A multi-dimensional (considering energy and monetary flows) and a multiple scale approach (studying a region, a country, socioeconomic subsectors) can result more useful to study similarities and differences among countries (Giampietro and Mayumi, 2000a). A sound accounting scheme therefore should embrace the complex picture of energy flows by integrating the analysis of energetic flows, with other biophysical entities (i.e. demographic variables) and economic flows across multiple scales. The concept of energetic performance has to be investigated from the perspective of the whole (such as countries themselves) or from the perspective of the smaller sub-compartments (such as individual subsectors) that compose of the society. To make things more difficult, it is also crucial to tackle the issue of data inconsistency in international statistics. The different international databases used by analysts have long been suffering from the lack of consensus and coherence, which implies a great difference in data resulting from different accounting schemes (differences between BP, UN, IEA, statistics; see OECD/IEA 2004). In relation to this point, an innovative accounting scheme is introduced in the next section.

2. THE METHODOLOGY: AN INNOVATIVE GRAMMAR OF ACCOUNTING FOR ENERGY FLOWS

The accounting of energy is a difficult task. In fact, the definition of “energy” - *the ability to generate a change in a given state space* – is impredicative in its nature. It has to be acknowledged that “energy” can only be measured and aggregated only after a pre-analytical definition of conversion factors over a given set of energy forms (Giampietro, 2006)). Therefore, the aggregation of different energy forms requires the choice of a criterion of equivalence (the definition of conversion factors).

As a matter of fact, the literature of energy analysis (energetics) reflects the historic struggle associated with the epistemological challenge of handling different energy forms (Alcántara and Roca, 1995; Ayres and Warr 2005; Cleveland, 1992; Cleveland et al. 2000; Cullen and Allwood, 2010; Giampietro and Mayumi, 2004; Hall et al. 1984; Kaufmann, 1992; Odum, 1971; 1996; Slesser, 1987; Ulanowicz, 1986).

To deal with this challenge it is necessary to adopt innovative analytical tools based on complex system thinking. Particularly useful is the concept of generating a ‘grammar’ capable of tracking the flows of energy across levels and referring to different energy forms (Giampietro et al, forthcoming). Starting from Primary Energy Sources (PES) **expressed in physical amounts** we can describe the first transformation needed to generate a flow of Energy Carriers (EC) - broadly categorized in this grammar into three categories of: *electricity*, *heat* and *fuel*. Then, a second transformation moving from Energy Carriers into a set of End Uses (EU). End uses are the functions expressed by society for its continued existence can be described. By adopting this distinction between different energy forms [PES → EC → EU → stabilization of society] in an energy chain, we can use data taken from energy statistics within a specific grammar. In this way, instead of being trapped in an ocean of data without meaning (plain numbers) we can extract meaningful representations looking for relevant external referents.

2.1 The PES – EC – EU scheme: The “grammar”

2.1.1 Primary Energy Sources (PES)

The boundaries of the system are defined by the definition of PES entering into the energy scheme. They can broadly be categorized by fossil fuels, renewable sources and nuclear sources (on the bottom of Fig. 2). The example in Fig. 2 refers to Spain indicating the various energy throughputs for the year 2003. PES are expressed in

biophysical quantities such as tones of Coal, kg of falling water for hydro, kg of uranium to operate nuclear plans at a certain capacity etc. The very concept of PES entails the existence of an external constraint that is affecting the metabolic pattern of the system either on the supply side or the sink side. For example, in the case of lack of uranium, nuclear energy would be impossible. In the same way, peak oil will affect the amount of oil entering the system limiting the generation of fuels or electricity. The issue of CO2 emissions indicates the existence of constraint operating on the sink side. It should be noted that it is possible to assign an energetic value to the biophysical quantity used to assess PES, however, this is at the basis of a lot of confusion. In fact, only after individuating a PES of reference – Tons of Oil Equivalent – we can assign an energetic equivalent to it and quantify PES in terms of Joules of energy (1 TOE = 42 GJ).

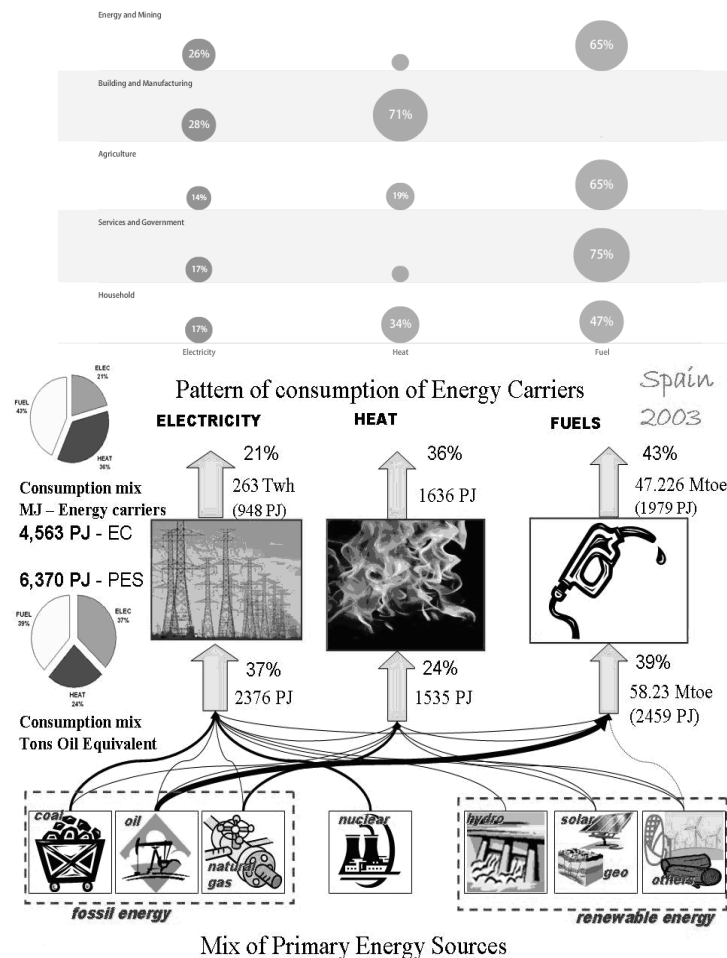


Fig. 2. The PES – EC – EU Scheme

Figure 2. Refers to our proposed scheme of energy accounting (the grammar) illustrating the various stages of the energy flow chain that have been defined, following the PES – EC – EU scheme (detailed explanations in: Giampietro et al., 2010).

2.1.2 Energy Carriers (EC):

Energy Carriers within our approach can be broadly categorized into three main types: electricity, heat and fuels. *Fuel and fuel derivatives* are namely products of crude oil and feedstock sources entering into refineries, which generate Gas/Diesel Oil, LPG Motor Spirit, Kerosene jet fuels etc. They represent the usable forms of fuel derivatives for the society (rather than crude oil itself). Evidently some of the energy is lost because of the transformation from crude oil into its possible products as well as some energy is consumed for the own operations of the machines. This explains why 1 MJ of EC have a cost in terms of MJ of PES. For obtaining *heating sources*, a great proportion of solid fuels (such as hard coal, coke), and a portion of petroleum

derivatives such as LPG and Naphtha, are used in coke ovens and blast furnaces for the generation of derived gas. This, combined with a great source of (usually imported) natural gas, would be the primary ingredients used for heating purposes. *Electricity generation* mainly originates from the PES sources that have been diverted to Thermal power plants (hard coal, lignite, derived gas, natural gas, refinery gas, gas/diesel oil and residual fuel oil). Other PES sources such as Biomass and industrial wastes are predominant contributors to electricity production as well. Hydro electricity and nuclear plants have differing generation profiles in different countries, yet are also prominent input sources entering into the system for electricity generation.

2.1.3 End Uses (EU):

The three main categories of possible forms of carriers are then potentially canalized for the required end uses to the society (as illustrated in the top of the Fig. 2). Within our multi scale approach the breakdown of the societal level of the economy to a lower level is represented by the sum of the socioeconomic sectors as the following: Household Sector (HH), Services and Government Sector (SG), Agriculture (AG), the Productive Sectors (PS) that are composed of the Building and Manufacturing (BM) and the Energy and Mining Sector (EM). By making a distinction over the carriers utilized by type of end use, it becomes possible to study the feasibility of desired output patterns (or even speculate on low carbon society via how much it is possible to reduce energy consumption, while keeping the same set of function required by society).

In practical terms we propose a dual system of accounting:

- (i) an accounting based on EC to check the feasibility of the expression of the set of functions required by society;
- (ii) an accounting based on PES (required to generate the needed mix of ECs) to check the compatibility with biophysical constraints (the availability of resources and the environmental impact) on the supply and sink side.

For example, as also seen in Fig 2, in the year 2003 Spain consumed 263 Twh of electricity, 1636 PJ of heat and 1979 PJ of fuel sources using 6370 PJ (TOE) of PES sources. Thus depending on the conversion factor of each carrier (e.g. assuming 3:1 ratio for electricity, 1.1:1 for heat and 1.2:1 for fuel), we can calculate the share of PES consumed by each sub-sector requiring a certain amount of carriers at a given mix.

3. EMPIRICAL APPLICATIONS AND COUNTRY PROFILES

3.1 Implementing the Grammar

Implementing this grammar for EU 14, allows us to visualize the mix and the diversity of primary energy supply sources in each country (in terms of PES), the subsequent flows of energy carriers (EC) and the mix required by the society in relation to the mix of end uses, determined by the range of functions that society has to express. The amount of useful energy generated using carriers defines the set of functions, which can be carried out by each society. This analysis can be carried out for each one of the compartments of the economy mentioned before. When performing this analysis we can see that different phases of economic and social development do entail: (i) different levels of consumption of ECs; and (ii) different mixes. Fig. 3 and 4 illustrate the situation in 1990 and 2007 for each sector of the 14 considered countries: (i) the overall size of the pies illustrates the level of EC consumption for each compartment; (ii) the relative size of the cloves, within each pie, indicates the mix of ECs.

3.1.1 Agricultural Sector and the EC mix

On average the typical European cluster agglomerates around an EC mix at: 60% fuel, 20% electricity and 20% heat sources for the agricultural sector. Fuel is mainly used for tractors and machinery in carrying out intense agricultural practices, followed by heating sources used for greenhouses. However, in some exceptional

cases other carriers dominate in such as heat in the Netherlands for 2007 at a value of 65%; or electricity, for the United Kingdom in 2007 at 40%. The results of this analysis reveal that the Netherlands is a clear outlier in terms of overall energy throughput (sum of all the ECs) for the agricultural sector in comparison to the rest of the EU countries, followed by France, Spain, Germany and Italy. Over the years, the AG sector has faced intensification in terms of energetic throughput however; in comparison with the rest of the sectors still has a very low throughput of energy – Refer to Fig. 3 and 4.

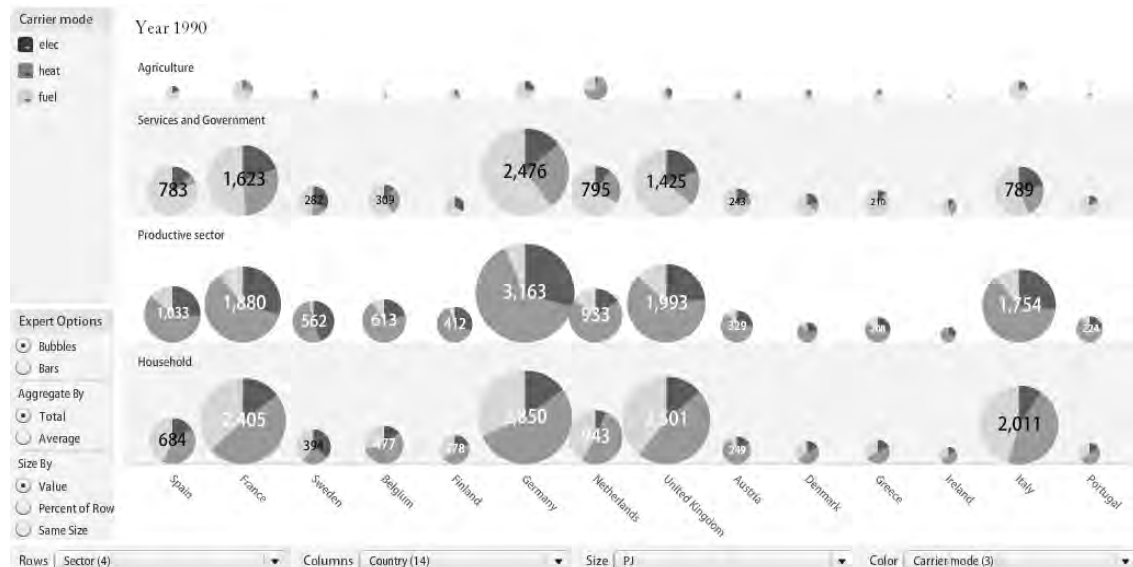


Fig. 3. Energy Carrier Mix Profiles per Sector per Country for 1990
(image generated by Many Eyes Programme IBM)

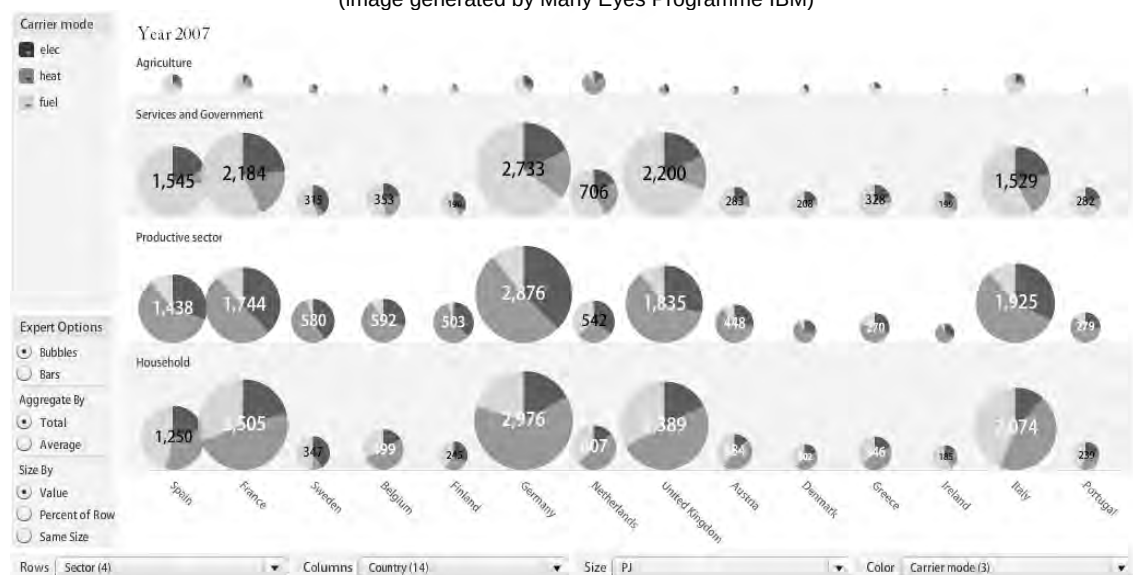


Fig. 4. Energy Carrier Mix Profiles per Sector per Country for 2007
(image generated by Many Eyes Programme IBM)

3.1.2 Productive Sector and the EC mix

The productive sectors are mainly dependent on heating sources that drive the industry, primarily used in intense manufacturing, steel production and other heavy industries and as such results to be the sector with the highest overall energy throughput. The requirement of electricity has increasingly been gaining importance in overall fraction over the period of the analysis. Yet, as observed throughout the 17 year period of analysis, countries such as France, Belgium, Germany, Netherlands and UK have decreased their overall total throughput of ECs in the productive sectors while very few countries such as Spain and Italy have increased their throughput in

productive sectors (namely due to building and construction activities that have boomed after the 90s).

3.1.3 Service Sector and the EC mix

Percentage-wise, the majority of the service sector is dominated by heating sources (used for heating buildings), fuel sources (in our grammar the transport sector - road and freight is included in the service sector), followed by electricity. In almost all of the countries the consumption of energy in the service sector has expanded immensely, indicating the clear transition from an economy based on the production of goods, to a more knowledge based society based on services.

3.1.4 Household Sector and the EC mix

The general percentage distribution of ECs illustrates a cluster at around an average value of: heat: 40-50%; electricity: 15-20% and fuel: 30-40% for the household sector. The fuel is clearly utilized for transportation due to a large private car ownership. The throughput of fuel in the household sector (in proportion to the rest of the carriers), is expectedly higher in countries with high private car ownership (e.g., Italy).

3.2 Linking the energy scheme to an integrated analysis

The representation of energy throughput across the various sectors with their relative composition of carriers makes it possible to extract a lot of relevant and meaningful information from energy statistics. However, it is also crucial to link such an accounting to the structural expression of functions, which we associated with the metabolic pattern of societies. Extensive variables such as the total energy throughput (TET) reveal information on the bulk quantity of energy use in a specific sector, yet do not present a relative benchmark value that makes it possible the comparison of the performance among different countries. For this task, the following intensive indicators have been developed making possible to compare the performance at the level of the specific sectors considered:

Variable	Definition
Exosomatic Metabolic Rate (MJ/hr) - EMR	MJ of energy carriers per hour of human activity
Economic Labour Productivity (€/hr) - ELP	Added value generated (in €) per hour of human activity in that sector (based on constant 2000 values)

In this way it is possible to cross correlate the performance of each country by looking at the relation between the level of energy throughput (MJ/hr) and the resulting Economic Labour Productivity (€/hr). This is illustrated in Fig. 5 for the EU 14 countries. The graph has on the X axis the Economic Labour Productivity (€/hr) and on the Y axis the Exosomatic Metabolic Rate (the energy throughput – measured in EC - consumed per hour in the sector – MJ/hr). The sizes of the bubbles illustrate the total amount of hours dedicated to each activity for each country. The performance is quite different over the various sectors considered, and in general a higher level of capitalization tends to be associated with a higher level of ELP (within each sector).

3.2.1 Metabolic Pattern of the Agricultural Sector

The EMR of the agricultural sector is observed highest in regions of traditionally intense practices, primarily led by the Netherlands, followed by Denmark and Sweden (this can greatly be linked to the high technical capitalization is due to cattle ranching for dairy purposes). In such countries, the economic output also results high potentially due to the option of export of such high quality cattle/dairy products.

3.2.2 Metabolic Pattern of the Productive Sector

The productive sector is the most intense sector in terms of energetic throughput per hour. Yet, clearly, depending on the type of manufacturing there is much variability within the sector itself. In fact, the activities can range from heavy industry and large manufacturing such as the steel, metallurgy, automotive sectors as seen for example in Austria and Belgium to “sophisticated manufacturing” including high tech industries (namely electronics) that require skilled labor such as in the Netherlands and Denmark. Evidently, the energy throughput that takes place between the two distinct forms of the PS sector and the resulting trade of in terms of economic gain will affect, at large, the metabolic performance of the sector. However, to carry out this “fine tuning” analysis, we should use data referring to lower level sub-sector, in order to be able to make a distinction between the size of the lower level consumption and the different mixes.

3.2.3 Metabolic Pattern of the Service Sector

The service sector has a relatively low energetic metabolic rate, clustering at around 60MJ/hr with very high economic output rates at an average of 40€/hr for the analyzed EU14 countries. Thus, economic performance in relation to energy consumption results the highest tradeoff in the service sector. This indeed explains why developed (European) countries have been shifting their heavy industries outwards, switching to a service based economy. Moreover, factors such as rising labour costs and higher energetic costs have pushed manufacturers to move to Eastern Europe or South East Asia and China. Such a drive toward cheaper production patterns have resulted in a massive externalization of the most energy intensive production process (the PS sector), which has given way to an important diversification in the service sector activities, paid for by an increasing dependency on import for the supply of required goods.

3.2.4 Metabolic Pattern of the Household Sector

The household sector, which does not contribute to the formal economy (within this system), has the lowest energy throughput per hour in comparison with the other sectors. This is due to the immense number of hours of human activities spent in this sector including activities such as eating, sleeping, personal care and household chores. Due to the high dependency ratio in modern societies (more than 50% of the population is not in the Paid Work sector) and the light work loads (about 1,800 hours/year, which is 10% of the total hours in a year), more than 90% of human activity of a modern society takes place in the household sector. An increase in the energetic throughput in this sector is usually linked to an increase in material standard of living. Highest values are found in Belgium, Austria, Finland and Ireland for the year 2007.

4. CONCLUSIONS

An analysis of the metabolic pattern of societies is a useful tool for analyzing society-environment interactions. It characterizes the efficiency of technology in guaranteeing an acceptable standard of living, via the conversions of ECs into the End Uses – the functions expressed by the various compartments of society. At the same time, when analyzing the conversion of PES into the required flow of EC it tracks the amount of raw materials extracted (and required) and waste generated in the production of EC. This makes it possible to estimate the severity of a variety of external biophysical constraints (remaining stocks for non-renewable energy sources, land, water and soil for biomass, falling water for hydroelectric power, etc.). Moreover, in cases of acute crises such as peak oil or that of climatic change, it provides a tool for analysis and exploration of the status quo and possible option spaces to predict upon. The, examples presented within the scope of this article, are few of the many potential areas of investigation and likely results that can be forecasted upon for energetic analysis with such an energy accounting scheme and integrated analyses. Moreover, inference from underlying patterns of the dynamic temporal patterns of county profiles are imperative for the policy domain and

future implications on energy security and possible energetic transformations for breaking the addiction to fossil energy.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support provided by the EU FP7 Project of SMILE - Synergies in Multi-scale Inter-Linkages of Eco-social systems FP7-SSH-2007-1 (Project no.217213).

REFERENCES

- Alcántara, V. and Roca, J. (1995) 'Energy and CO₂ emissions in Spain', *Energy Economics*, 17-3, pp. 221–230.
- Ayres, R.U. and Warr, B. (2005) 'Accounting for growth: The role of physical work', *Structural Change and Economic Dynamics*, vol 16, no 2, pp 181-209
- Cleveland, C. J. (1992) 'Energy quality and energy surplus in the extraction of fossil fuels in the U.S.', *Ecological Economics*, vol 6, pp 139-162
- Cleveland, C.J., Kaufmann, R. and Stern, S.I. (2000) 'Aggregation and the role of energy in the economy', *Ecological Economics*, vol 32, pp 301–317
- Cullen, J.M., Allwood, J.M. (2010) "The efficient use of energy: Tracing the global flow of energy from fuel to service", *Energy Policy* 38 (2010) pp. 75–81
- Fischer-Kowalski, M. (1998) 'Societal metabolism: The intellectual history of material flow analysis part I, 1860-1970', *Journal of Industrial Ecology*, vol 2, no 1, pp 61–78
- Giampietro, M. (2006) 'Theoretical and practical considerations on the meaning and usefulness of traditional energy analysis', *Journal of Industrial Ecology* vol 10, no 4, pp 173-185
- Giampietro, M. and Mayumi, K. (2000a) 'Multiple-scale integrated assessment of societal metabolism: Introducing the approach', *Population and Environment*, vol 22, no 2, pp 109–153
- Giampietro, M. and Mayumi, K. (2000b) 'Multiple-scales integrated assessments of societal metabolism: Integrating biophysical and economic representations across scales', *Population and Environment*, vol 22, no 2, pp 155–210
- Giampietro, M. and Mayumi, K. (2004) 'Complex systems and energy', in C. Cleveland (ed) *Encyclopedia of Energy*, vol. 1, Elsevier, San Diego, CA, pp. 617-631
- Giampietro, M. and Ramos-Martin, J. (2005) 'Multi-scale integrated analysis of sustainability: a methodological tool to improve the quality of the narratives', *International Journal of Global Environmental Issues*, vol 5, no. 3/4, pp 119–141
- Giampietro, M., Mayumi, K., Sorman, A.H. (forthcoming) *The Energetics of Modern Societies* Springer
- Giampietro, M., Mayumi, K., Sorman, A.H. (2010) "Assessing the quality of alternative energy sources: Energy Return On the Investment (EROI), the Metabolic Pattern of Societies and Energy Statistics"; (ICTA) Working Papers on Environmental Sciences; Available Online: <http://www.recercat.net/handle/2072/16099>
- Hall, C.A.S., Cleveland, C.J. and Kaufman, R. (1986) *Energy and Resource Quality*, John Wiley & Sons, New York
- Kaufmann, R. K. (1992) "A Biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change". *Ecological Economics* 6(1) 35-56.
- Martínez Alier, J.; Schüppmann, K. (1987) *Ecological Economics: Energy, Environment and Society*. Basil Blackwell, Oxford ISBN: 0-631-15739-5
- Odum, H.T. (1971) *Environment, Power and Society*, Wiley-Interscience, New York, NY
- Odum, H.T. (1996) *Environmental Accounting: Energy and Environmental Decision Making*, John Wiley, New York, NY
- OECD/IEA, (2004) *Energy Statistics Manual*; Available Online: http://www.iea.org/textbase/nppdf/free/2004/statistics_manual.pdf
- Slesser, M., 1987, "Net energy as an energy planning tool", *Energy Policy*, June 1987, pp. 228 – 238
- Ulanowicz, R.E. (1986) *Growth and Development: Ecosystem Phenomenology*, Springer-Verlag, New York, NY.

SESSION 1.2

URBAN METABOLIC PATTERNS

Hall M. H.

POSITIONING RUST BELT CITIES FOR A SUSTAINABLE FUTURE: STEP 1,
AN EVALUATION OF NEIGHBORHOOD SOCIO-ECOLOGICAL METABOLISM

Fath B. D., Zhang Y., Yang Z., Li S.

URBAN ENERGY METABOLISM USING ECOLOGICAL NETWORK ANALYSIS:
CASE STUDY OF FOUR CHINESE CITIES

Basireddy, S. R. and Nathan, H. S. K.

ENERGY INFRASTRUCTURE FOR A HIGH HUMANE AND LOW CARBON
FUTURE

POSITIONING RUST BELT CITIES FOR A SUSTAINABLE FUTURE: STEP 1, AN EVALUATION OF NEIGHBORHOOD SOCIO-ECOLOGICAL METABOLISM

*Myrna H. Hall**

SUNY, College of Environmental Science and Forestry, Syracuse, NY, USA

Background/Question/Methods: Long Term Socio-Ecological Research encompasses both the cultural and economic realms that comprise the human dimension of ecosystem studies. Socio-ecological metabolism analysis is a means of showing the connectivity, relative importance, and to some degree similarity of all city processes, whether strictly biophysical or social, in order to facilitate planning for a more secure urban future. We hypothesize that the socio-ecological metabolism (SEM) of a North-Eastern rust belt city may be vulnerable to future external factors such as restrictions in oil availability, or both climate-induced heating and northward migration, and that city revitalization emphasizing natural ecosystem processes via green infrastructure can impact SEM positively at both the city/regional and the household/neighborhood level in the future. At the neighborhood scale we calculate average ecological production based on LiCor 6400 in situ measurements and leaf area index (LAI) for different tree species. Ecological respiration is derived from home energy use statistics from local utilities, average household food consumption by income group, and Syracuse urban transportation statistics derived from the local Transportation Council. We combine 2000 census block data (US Census 2000) on income, age, and ethnicity, and tax parcel data on owner occupied homes, renter occupied homes and vacant homes to derive an estimate of sociological production.

Results/Conclusions: We survey urban residents to determine their willingness to install green infrastructure (trees, rain gardens, rain barrels, etc.) on their properties. Through map overlay we illustrate by census block neighborhood SEM along gradients of green plant production and both biotic and fossil energy consumption (respiration) (both in MJ ha⁻¹). Mapped projections based on citizen attitudes and biophysical capacity for GI implementation allow us to assess urban opportunities for potential SEM enhancement. Our models will allow citizens and decision makers to see how SEM at this scale can change as a function of alternate LULC management options and changing energy inputs.

* E-mail: mhhall@esf.edu

URBAN ENERGY METABOLISM USING ECOLOGICAL NETWORK ANALYSIS: CASE STUDY OF FOUR CHINESE CITIES

Brian D. Fath^{*1,2}, Yan Zhang³, Zhifeng Yang³, Shengsheng Li³

¹ Biology Department, Towson University, Towson, Maryland, USA

² Dynamic Systems, IIASA, Laxenburg, Austria

³ School of Environment, Beijing Normal University, Beijing, 100875

ABSTRACT

We develop an ecological network model for urban systems using throughflow and utility analyses. The model uses compartments based on five sectors (energy exploitation, energy transformation, industry, households, and recovery). The trophic levels include energy producers, primary consumers, secondary consumers, and decomposers. The goal is to understand the metabolic system's network structure and the ecological relations (i.e., mutualism, competition, etc.). The structure is derived from the weight distribution in the flow matrix, and the relations from the utility matrix. Four Chinese cities are used as examples (Beijing, Shanghai, Tianjin, and Chongqing). All four cities analyzed show an inverted pyramid structure in that producers were lower in total flow than consumers, which is consistent with the idea of cities as metabolic consumers on the landscape, and opposite to that of ecological systems which are supported by a large amount of producer flows. Regarding the ecological relations, Beijing had the highest mutualism index, followed by Shanghai, Tianjin, and Chongqing. Analyzing the structure and functioning of the urban energy metabolic system revealed suggestions for optimizing its structure and adjusting relationships among compartments, demonstrating how ecological network analysis can be used in future urban system research.

Keywords: urban metabolism; energy flow; network analysis; throughflow; utility analysis

1. INTRODUCTION

Cities are complex adaptive systems. Jacobs (1961) was an early pioneer into the study of urban systems as such in which the interconnections and design structure, as much as anything, influenced the socio-economic behavior and the subsequent life quality experienced by its inhabitants. She stated that urban planning is a problem in handling organized complexity, and viewed urban dynamics as an intricate and close-grained diversity of uses. In this manner, she was laying the groundwork for comparing urban system function with ecological system function. There has been much research over the past decades investigating organisms (e.g., Brown 1995) and ecosystems as complex adaptive systems (e.g., Patten et al. 2002) and the consequences that has for understanding and managing them. Specifically, one can focus on the energy-matter needs that ecosystems have and the dynamic tendencies they undergo during development. One useful aspect is when we assume that ecosystems are exemplar systems of sustainability, having adjusted, adapted, and persisted during long time periods under varying environmental conditions (which they themselves create). Therefore, a lesson to learn is to apply ecological design principles to urban and industrial systems. This refers to the respect for diversity and the structural patterns that ensure functional properties in terms of energy, matter, and information flows. This application of ecological principles to anthropogenic systems has been termed socio-metabolism to refer

* Corresponding author; E-mail: bfath@towson.edu; Tel+1-410-704-2535

to the concept that societies are also ecological and resource dependent and resource consuming systems.

Urban systems concentrate the energy flows from surrounding areas in order to support the intense and diverse activities occurring within them. They are open systems, which continually require replenishment of energy and matter to sustain these activities. They acquire the resources through a complex network of channels delivering everything from food, fuels, water, air, materials, etc., and removing the wastewater, waste heat, solid waste, as well as the finished goods and services for export. With energy as the main driver for ecological and social systems, it is important to understand the energy flows within both. In ecological systems, one finds an abundance of primary producing organisms, whose role it is to capture and import external energy resources into the system. These stored solar energy resources are transformed and transferred to the primary and secondary heterotrophic consumers. The role of decomposers in the ecological system is to utilize remaining energy and provide closure in order to maximize the energy throughflow, cycling, and retention time (Fath et al. 2001). Urban systems have the same need for these energy carrying and transforming sectors. In this study, we apply ecological principles and network analysis to investigate the thermodynamic patterns in four Chinese cities.

2. CITY AS A SOCIO-METABOLIC SYSTEM

As urbanization accelerates, energy use in urban areas is expected to increase rapidly. In the 11th Five-Year Plan (2006-2010), China considers reducing the country's energy consumption per unit GDP by 20%. As the main site of energy consumption, cities have become the focus of considerable attention, with the goal of adopting concrete measures to reduce urban energy consumption. At present, the most effective way to identify weak links in an urban energy system is to study energy consumption from the perspective of energy metabolism.

By studying urban energy metabolic processes using network analysis, we can track all the key links in a city's energy metabolism. *Ecological network analysis* is currently one of the main methods for analyzing the interactions between an ecosystem's structure and function. By quantifying the metabolic fluxes, analyzing the relationships between metabolic components, and analyzing the structure and function of the urban energy metabolic system, it becomes possible to define the status and function of the urban metabolic components. Ecological network analysis has been widely applied to study natural ecosystems, but has seldom been used in the analysis of urban ecosystems (Bodini and Bondavalli, 2002; Bailey et al., 2004a, b; Zhao, 2006; Zhang et al. 2010).

In this paper, we develop an ecological network model of an urban energy metabolic system by collecting, sorting, and analyzing the available energy consumption data. The model can reflect the whole process of energy consumption from resource development, exploitation, transformation, and consumption to recovery. Using the model, we developed a new method for studying the internal characteristics of an urban energy metabolic system, with the goal of providing both theoretical and practical methods for optimizing and managing energy in Chinese cities. An extended version of this analysis is published in Zhang et al. (2010).

3. METHODOLOGY AND DATA USED

3.1 Processes involved in urban energy metabolism

The match between ecological functions and social functions is not isomorphic, but here we assume that the urban system sectors energy exploitation, energy transformation, household and industrial consumers, and recovery represent relevant analogous ecological roles. Specifically, the energy exploitation sector mirrors the primary producers, the energy transformation sector represents the primary consumers, the

household and industrial sectors are secondary consumers and the energy recovery sector represents the decomposers as shown in the conceptual model in Figure 1.

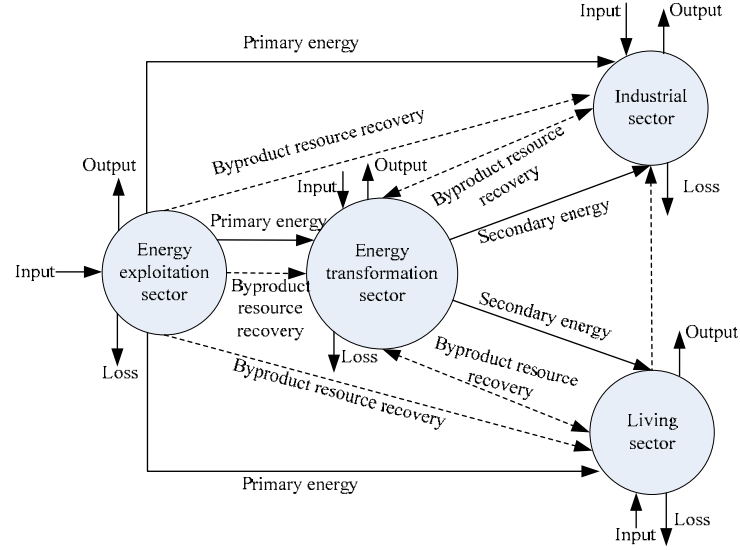


Figure 1. Conceptual model of urban energy metabolic processes.

3.2 Ecological network model of the urban energy metabolism

By analyzing urban energy metabolism processes in the conceptual model, it is determined that the sectors are linked together by a network of 16 flows that reflect the metabolic pathways among these five compartments (Figure 2). According to the direction of the energy flow, all energy flows among compartments can be represented by directional lines that connect the nodes in the network, resulting in an ecological network model for the urban energy metabolism system (Zhang et al., 2009a, b).

Using the standard coal equivalent coefficient (Co) values, we converted all energy types that flowed among compartments into standard coal equivalents (kgce), and based on these values, calculated the direct metabolic flows for each compartment in the model. Table 1 presents the resulting matrices for the direct metabolic flows for Beijing (F_B), Shanghai (F_S), Tianjin (F_T), and Chongqing (F_C).

Note that in this diagram, f_{ij} represents the flow from compartment j to compartment i , z_i represents the flow into compartment i from outside of the energy metabolic system, and y_i represents the boundary outflows from compartment i .

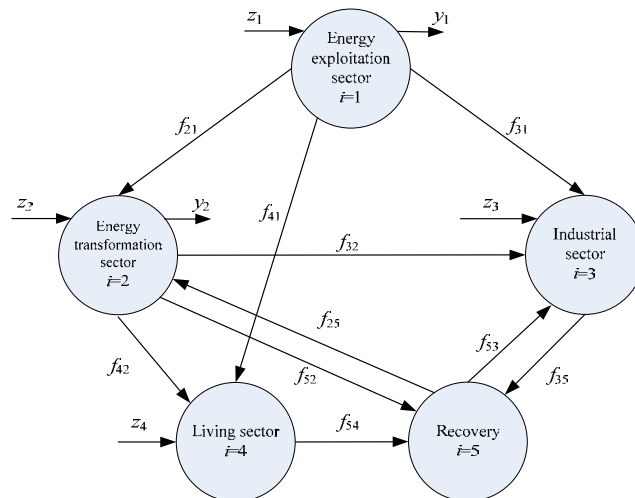


Figure 2. The ecological network model of urban energy metabolism system used in the present study.

Table 1. Matrices for the direct ecological flows among compartments (units: 10^7 t standard coal equivalent). For the five components, the i values are in the first column of the table, and the j values are across the top of the table.

Beijing (F_B)						
	1	2	3	4	5	T
1	0	0	0	0	0	0.459
2	0.087	0	0	0	0	3.466
3	0	1.929	0	0	0	4.629
4	0	0.080	0	0	0	0.729
5	0	0	0	0	0	0

Shanghai (F_S)						
	1	2	3	4	5	T
1	0	0	0	0	0	0.459
2	0.093	0	0	0	1.036	3.466
3	0.009	2.946	0	0	0.008	4.629
4	0	0.143	0	0	0	0.729
5	0	0.004	1.032	0.008	0	0

Tianjin (F_T)						
	1	2	3	4	5	T
1	0	0	0	0	0	2.916
2	0.517	0	0	0	0.080	6.438
3	0.024	1.045	0	0	0.119	3.107
4	0	0.175	0	0	0	0.369
5	0	0	0.199	0	0	0.199

Chongqing (F_C)						
	1	2	3	4	5	T
1	0	0	0	0	0	3.906
2	1.425	0	0	0	0.082	1.515
3	1.514	0.627	0	0	0.346	3.152
4	0.106	0	0	0	0	0.328
5	0	0.001	0.427	0	0	0.427

3.3 Network utility analysis

Network utility analysis is an ecological network approach that was first introduced by Patten (1991) to express the relative benefit to cost relations in networks. In this method, a direct utility matrix is constructed and used to analyze the network functions (Fath, 2007). From the urban network structure that we derived, we analyzed the mutual relationships between elements of the network. In the network utility analysis, d_{ij} represents the utility of an inter-compartment flow from compartment j to compartment i , and can be expressed as:

$$d_{ij} = (f_{ij} - f_{ji}) / T_i \quad (1)$$

where f_{ij} represents the flow from compartment j to compartment i , f_{ji} represents the flow from compartment i to compartment j , and T_i is the sum of the intercompartmental and boundary inputs into compartment i . From the matrix D , which contains all d_{ij} values, a dimensionless integral utility intensity matrix $U = (u_{ij})$ can be computed from the following convergent power series:

$$U = (u_{ij}) = D^0 + D^1 + D^2 + D^3 + \dots + D^k + \dots = (I - D)^{-1} \quad (2)$$

where I is the identity matrix, u_{ij} represents the integral dimensionless value of d_{ij} , which is calculated using a Leontief inverse matrix, and the matrix U represents the intensity and pattern of integrated relations between any of the five compartments in the network (i.e., the utility, u_{ij}).

In network utility analysis, the sign of an element in matrix U can be used to determine the interaction pattern between compartments in the network to derive a mutualism index (M). The mutualism index of the urban energy metabolic system can be expressed as follows:

$$M = J(U) = S_+/S_- \quad (4)$$

Here, $S_+ = \sum_{ij} \max(\text{sign}(u_{ij}), 0)$ and $S_- = \sum_{ij} (-\min(\text{sign}(u_{ij}), 0))$ (Fath, 2007; Lobanova *et al.*, 2009). If the matrices have more positive signs than negative signs, this means that the urban ecological system exhibits mostly positive relationships between compartments and thus represents network mutualism (Fath, 2007).

During the analysis of urban metabolic relationships based on the sign distribution and the ratio of the numbers of positive and negative signs in the network utility matrix, we can therefore identify five intercompartmental ecological relationships: competition, exploitation, control, mutualism, and neutrality. Using the results of this analysis, we can identify potential directions for optimizing a city's energy metabolic system toward greater mutualism.

4. RESULTS AND DISCUSSION

4.1 Urban metabolic structure

Based on the energy metabolic flows among the compartments, we calculated the integral output flow matrices and the weight matrices for Beijing, Shanghai, Tianjin, and Chongqing, respectively. Based on these results, the role, status, and function of each compartment can be defined.

Chongqing had the highest weight for energy production (compartment 1), followed by Tianjin, Beijing, and Shanghai, which indicates that the city's energy supply capability is high (Figure 3). Beijing had the highest weight for primary consumers (compartment 2), followed by Tianjin, Shanghai, and Chongqing, which means that inputs for the energy transformation sector in Beijing are relatively large. Shanghai had the highest weight for secondary consumers (compartments 3+4), followed by Beijing, Tianjin and Chongqing, which means that Shanghai's energy demand is relatively large. Shanghai had the highest weight for recovery (compartment 5), followed by Chongqing, Tianjin, and Beijing, which reflects the city's relatively strong self-regulation ability. Shanghai had the highest weight for industrial consumption (compartment 3), followed by Beijing, Tianjin, and Chongqing. Beijing had the highest weight for households consumption (compartment 4), followed by Shanghai, Chongqing, and Tianjin.

A healthy structure for an urban energy metabolism should be a clear pyramidal structure, with sufficient energy producers at the bottom of the ecological structure, followed by primary consumers (here, the energy transformation sector), and with a smaller weight of secondary consumers at the top. However, the ecological structure of Shanghai represented an inverted pyramid, and the structures of Beijing and Tianjin represented irregular inverted pyramids. In contrast, Chongqing showed an irregular pyramidal structure, but with producers and secondary consumers roughly in balance, and a lesser weight of primary consumers.

Urban energy metabolism systems change the energy flow patterns since they typically have little self-regulation ability. In the present study, the weight of the decomposers component was $\leq 5\%$ for all four cities. The proportion of decomposers can reflect the self-regulation ability of such systems, and in terms of the recovery weights, Shanghai had the highest self-regulation ability, followed by Chongqing, Tianjin, and Beijing, which means that Shanghai had the strongest recovery ability and Beijing had the weakest.

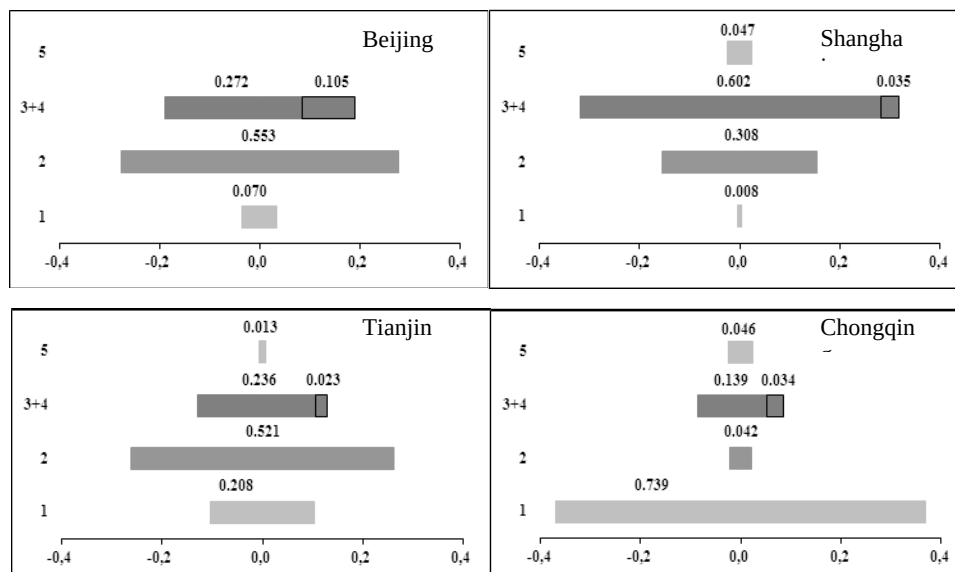


Figure 3. The ecological structure of the urban energy metabolic system for the four Chinese cities used in the case studies. Compartments: 1, energy exploitation sector; 2, energy transformation

sector; 3, industrial sector; 4, households sector; 5, recovery sector. The lengths of the bars have been normalized so that each bar or segment of a bar represents the proportion of the total flow (which equals 1.0) for that component.

4.2 Metabolic relationships

Using the metabolic flows among compartments, we calculated the integral utility matrices among compartments for Beijing, Shanghai, Tianjin, and Chongqing (U_B , U_S , U_T , and U_C , respectively) using network utility analysis. Based on the signs of the elements in the U matrices for the four cities, we have also presented the $\text{sgn}(U)$ values for each city in Table 2. We have presented this discussion for Beijing to illustrate how the data in Table 2 should be interpreted. Readers can easily use the same approach we have used for Beijing to examine details of the relationships for the other three cities.

For Beijing, the ecological relationship between the energy exploitation and transformation sectors, between the industrial and energy transformation sectors, and between the households and energy transformation sectors, were exploitation, with $(su_{21}, su_{12}) = (+, -)$, $(su_{32}, su_{23}) = (+, -)$, and $(su_{42}, su_{24}) = (+, -)$. This indicates that local energy has been used to meet the demand for secondary transformation of energy, and likewise, the transformed energy was subsequently used in mass consumption by the industrial and households sectors. Increased pressure on the energy supply and transformation results.

Table 2. The integral utility matrices and the corresponding sign matrices for the urban energy metabolic systems of the four cities. For the five components, the i values are in the first column of the table, and the j values are across the top of the table.

Beijing $\text{sgn}(U_B)$					
	1	2	3	4	5
1	+	-	+	+	0
2	+	+	-	-	0
3	+	+	+	-	0
4	+	+	-	+	0
5	0	0	0	0	0

Shanghai $\text{sgn}(U_S)$					
	1	2	3	4	5
1	+	-	+	+	-
2	+	+	-	-	+
3	+	+	+	-	-
4	+	+	-	+	+
5	-	-	+	+	+

Tianjin $\text{sgn}(U_T)$					
	1	2	3	4	5
1	+	-	+	+	-
2	+	+	-	-	+
3	+	+	+	-	-
4	+	+	-	+	+
5	-	-	+	+	+
6	+	-	+	+	-

Chongqing $\text{sgn}(U_C)$					
	1	2	3	4	5
1	+	-	-	-	-
2	+	+	-	-	+
3	+	+	+	-	-
4	+	-	-	+	-
5	-	-	+	+	+
6	+	-	-	-	-

The ecological relationship between the industrial sector and the households sector was competition, with $(su_{43}, su_{34}) = (-, -)$, indicating both sectors are vying to utilize primary and secondary energy. This competition between the households and industrial sectors occurred in all four cities, which could create further stress for urban development if energy supplies are not adequately available for both sectors.

The ecological relationships between the industrial and energy exploitation sectors and between the households and energy exploitation sectors for Beijing were $(su_{31}, su_{13}) = (+, +)$, and $(su_{41}, su_{14}) = (+, +)$, reflecting the mutualisms between the industrial sector and local energy exploitation and between the households sector and local energy exploitation; this means that the industrial and households sectors mainly utilize the energy transformation sector.

The ecological relationships between the recovery and energy exploitation sectors, between the recovery and energy transformation sectors, between the recovery and industrial sectors, and between the recovery and households sectors, were neutral for Beijing, with $(su_{51}, su_{15}) = (0, 0)$, $(su_{52}, su_{25}) = (0, 0)$, $(su_{53}, su_{35}) = (0, 0)$, and $(su_{54}, su_{45}) = (0, 0)$, reflecting the lack of a recovery sector in Beijing and the resulting lack of interactions between this sector and the other sectors.

Based on the integral utility intensity matrix (U) values, Beijing's mutualism index (2.20) was higher than that of Shanghai and Tianjin (both 1.78), and much higher than that of Chongqing (0.92). The reason Chongqing's mutualism index was less than 1 is because of the greater frequency of exploitation relationships between sectors. Thus, the urban energy metabolic processes of three of the four cities reveal an overall degree of mutualism, with mutualism indices greater than 1, but differences in the ecological relationships among the compartments lead to large differences in these indices.

5. CONCLUSIONS

Using ecological network analysis, we constructed a simple network model for urban energy metabolism, and used the model to analyze the urban energy metabolic system of four Chinese cities. The approach let us analyze the processes inherent in the urban energy metabolic system from the perspective of energy flows, thereby providing insights into the ecological relationships between compartments of the model. The results show that this method can be used in future studies of other urban systems. The main conclusions from the analysis are: 1) the *energy trophic structure* of the four cities was largely inverted, and 2) three of the four cities showed *mutualism relationships*. Furthermore, some of the energy metabolic relationships between sectors were similar for all four cities, whereas others differed.

Based on the detailed insights provided by our results, we have the following recommendations to improve energy utilization by the four cities. Chongqing should improve the energy utilization efficiency of the secondary consumers, whereas Tianjin and Shanghai should restrict the currently excessive development of their energy transformation sectors, and Beijing should adjust its energy structure to promote the utilization of recovered energy, which is currently nonexistent. The cities should all reduce their excessive exploitation of local energy by the primary and secondary consumers, and reduce competition for energy between the industrial and households sectors. They should also reduce the excessive exploitation of the external environment's resources by the industrial and energy transformation sectors, and should promote the recovery of local energy and the exploitation of renewable energy.

Although metabolic paths in urban energy metabolic systems are more complex than the ecological network model developed in this study, the model nonetheless provides a useful way of analyzing the system's main components and their functional relationships. Using throughflow and utility analyses, we revealed the structures of the systems and the types of ecological relationships between their components, and were able to use the results to interpret the problems facing a given urban system and recommend directions for future management. Future optimization of the model should provide a more precise simulation of the complexity of real urban energy systems.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (No. 40701004), the Ph.D. Program Foundation of the Ministry of Education of China (No. 20070027033), and the National Basic Research Program of China (973 Program, Grant No. 2005CB724204).

REFERENCES

- Bailey, R., Allen, J.K., Bras, B., 2004a. "Applying ecological input-output flow analysis to material flows in industrial systems. Part I: tracing flows". *Journal of Industrial Ecology* 8(1), 45–68.
- Bailey, R., Bras, B., Allen, J.K., 2004b. "Applying ecological input-output flow analysis to material flows in industrial systems. Part II: flow metrics". *Journal of Industrial Ecology* 8 (1), 69–91.

- Bodini, A., Bondavalli, C., 2002. "Towards a sustainable use of water resources: a whole-ecosystem approach using network analysis". *International Journal of Environment and Pollution*, 18(5), 463–485.
- Brown JH. 1995. "Organisms and species as complex adaptive systems: Linking the biology of populations with the physics of ecosystems". In: Jones, C. Lawton, J.H. (eds). *Linking Species and Ecosystems*, Chapman and Hall, London.
- Fath BD, Patten BC, Choi JS. 2001. "Complementarity of ecological goal functions". *J. Theoretical Biology* 208(4), 493–506.
- Fath, B.D., 2007. "Network mutualism: Positive community-level relations in ecosystems". *Ecological Modelling* 208(1), 56–67.
- Jacobs, J. 1961. *The death and life of great American cities*. The Modern Library, New York.
- Lobanova, G., Fath, B.D., Rovenskaya, E., 2009. "Exploring simple structural configurations for optimal network mutualism". *Communications in Nonlinear Science and Numerical Simulation* 14, 1461–1485.
- Patten, B.C. 1991. "Network ecology: indirect determination of the life-environment relationship in ecosystems". In: Higashi M. and Burns T. P. (editors) *Theoretical studies of ecosystems: the Network Perspective*. Cambridge University Press, Cambridge.
- Patten BC, Fath BD, Choi JS. 2002. "Complex adaptive hierarchical systems—background". In: Costanza R, Jorgensen SE (eds.). *Understanding and Solving Environmental Problems in the 21st Century*, Elsevier Science Ltd, London, England, pp. 41–94.
- Zhang, Y., Yang, Z.F., Yu, X.Y., 2009a. "Ecological network and emergy analysis of urban metabolic systems: Model development, and a case study of four Chinese cities". *Ecological Modelling*, 220(11), 1431–1442.
- Zhang, Y., Yang, Z.F., Yu, X.Y., 2009b. "Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China)". *Ecological Modelling*, 220(13–14), 1690–1696.
- Zhang Y , Yang Z, Fath BD, Li S. 2010. "Ecological network analysis of an urban energy metabolic system: model development, and a case study of four Chinese cities". *Ecological Modelling* 221, 1865–1879.
- Zhao, W., 2006. *Emergy structure analysis, optimization and regulation in an urban ecological economic system* [D]. Ph.D. Dissertation, Beijing Normal University, Beijing (in Chinese).

ENERGY INFRASTRUCTURE FOR A HIGH HUMANE AND LOW CARBON FUTURE

B. Sudhakara Reddy^{*1} and Hippu Salk Kristle Nathan^{*2}

*Indira Gandhi Institute of Development Research
Goregaon (E), Mumbai 400 065, INDIA*

ABSTRACT

Presently India is facing the twin challenge of energy universalization as well as emission reduction. Nearly 0.4 billion people in India— mostly residing in rural areas— do not have access to electricity and more than 0.8 billion people do not use modern cooking fuels. Provision of energy services however needs to take into account the global temperatures rise, which if to be limited to 2°C more from its pre-industrial value, Green House Gas (GHG) emissions must be halved by 2050 from its 1990 level. Energy infrastructure plays a key role to meet this dual challenge of universalization of energy services and reduction of energy-induced emissions. Assessing India's infrastructure, this study presents the high humane (Energy universalization) and low carbon scenarios and discusses investment needs, financing mechanisms and the key policy issues.

Keywords: Energy, Environment, Infrastructure, Universalisation

1. INTRODUCTION

Asia is driving the world energy markets, largely propelled by demand in China and India. As per International Energy Agency (IEA, 2008) estimates, the world energy consumption will increase by 45% in 2030 from its 2006 level, and India will account for 13.5% of that growth. India's high energy demand is driven by its high growth path. India is also characterized by a large populace who is deprived of modern energy services; 45% rural households and 7.8% urban households do not have access to electricity and 90% rural households and 33% of urban households do not use clean cooking fuel (NSSO, 2007). To attain energy universalization and sustain growth, India needs to step up its energy use. However, like other developing countries, India is constrained by the environmental consequences of energy use. Energy, which accounts for about 60% of Green House Gas (GHG) emissions, has a strong linkage with climate. To limit the global temperature to 2°C more from its pre-industrial value, the global GHG emissions must be halved by 2050 from its 1990 level (EU, 2008). Appropriate energy infrastructure is the answer to India's twin challenge of energy universalization and climate mitigation.³ Provision of secure, adequate, low-cost energy of quality and convenience in an environmentally benign manner is core to energy infrastructure.

After introducing the relevance of energy infrastructure this paper presents the energy demand outlook under low carbon scenario vis-à-vis baseline. The low carbon scenario is characterized by increased use of renewables through solar, wind, geothermal, biomass and hydro – which will reduce fossil-fuel demand. Then the paper presents the high humane scenario, which corresponds to energy universalization for domestic sector – i.e. providing all households with electricity for lighting and LPG and biogas for cooking. The study will also identify the actors and analyze their roles in

^{*} Tel: +91-22 2841 6526, Fax: 022 2841 6399, E-mail: sreddy@igidr.ac.in

^{2*} Tel: +91-9867582994, Fax: 022 2841 6399, E-mail: hnathan@igidr.ac.in

³ Energy infrastructure means the infrastructures associated with energy system from cradle to grave; i.e. from extraction to end use and disposal.

achieving the low carbon energy infrastructure goals. The financial model to attain the required infrastructure investment will be outlined with emphasis on barriers and drivers. The study concludes with discussion on key policy issues.

2. ENERGY INFRASTRUCTURE

Energy infrastructure can be primarily classified into following categories: infrastructure required for (i) exploration, development and extraction of energy sources (example: mining infrastructure, dams) (ii) transportation of raw natural resources to the generation unit (example: coal carrying trains) (iii) transformation of energy that turn raw material into useful energy products (example: power plants, oil refining units) (iv) transmission and distribution of energy to consumers (example: network of pipes for oil and natural gas, electricity transmission lines). The current energy infrastructure in India is grossly inadequate from both energy universalization and low carbon point of views. It necessitates immediate attention not only to add new infrastructure but also to modernize and improve the systems for brining about efficiency in production, processing, transmission and distribution and reduce the gap between supply and demand. Financing of energy infrastructure remains a major concern as experience shows that finance from traditional sources of funding would be insufficient to meet the demand and there would be need for innovative options such as carbon finance, fossil fuel subsidy re-orientation, streamlined Global Environment Facility (GEF) and Clean Development Mechanism (CDM) funds.

3. ENERGY DEMAND OUTLOOK

Table 1 gives the energy consumption in India met by different primary energy sources (Planning Commission, 2008). In the last five decades, the PEC (primary energy consumption) has increased that many times with a CAGR (compound annual growth rate) of 3.4%. The share of oil has remained around one-third of commercial fuel since 1970; however the share of natural gas increased from mere 1% in 1970-71 to 8.8% in 2006-07. The share of hydro has peaked in 1980s and now is on the decline. Nuclear energy, on the contrary, steadily increasing its share and emerging as an alternative to fossil fuels. Between 1990–91 and 2006–07, PCE registered a CAGR of 3.8%, whereas the commercial energy consumption grew at 4.9% suggesting a decline in growth rate of non commercial energy sources. This indicates a gradual shift towards commercial fuels, particularly in urban areas.

Table 1. Primary energy demand in India (MTOE)

Type of carrier	1960-61	1970-71	1980-81	1990-91	2000-01	2006-07	2011-12 [#]
Coal [*]	35.7 (79.9)	37.3 (62.3)	58.2 (60.2)	97.7 (55.9)	138.0 (49.1)	208.7 (53.3)	283 (51.8)
Oil [*]	8.3 (18.6)	19.1 (32.0)	32.3 (33.4)	57.8 (33.1)	107.0 (38.1)	132.8 (33.9)	186 (34.1)
Natural gas [*]	0.0 (0.0)	0.6 (1.0)	1.41 (1.5)	11.5 (6.6)	25.1 (8.9)	34.6 (8.8)	48 (8.8)
Hydro [*]	0.7 (1.5)	2.2 (3.6)	4.0 (4.1)	6.2 (3.6)	6.4 (2.3)	9.8 (2.5)	12 (2.2)
Nuclear [*]	0.0 (0.0)	0.6 (1.1)	0.8 (0.8)	1.6 (0.9)	4.41 (1.6)	4.86 (1.2)	17 (3.1)
Total Commercial [^]	42.8 (36.5)	60.3 (41.0)	99.8 (47.9)	181.1 (59.7)	296.1 (68.4)	391.5 (72.6)	546 (76.4)
Non-Commercial [^]	74.4 (63.5)	86.7 (59.0)	108.5 (52.1)	122.1 (40.3)	136.7 (31.6)	147.6 (27.4)	169 (23.6)
Total	117.2	147.1	208.3	303.2	432.8	539.1	715

[#] Projected requirement at the end of the Eleventh Plan as per the Integrated Energy Policy Report (IEPR) report

^{*} The number in the bracket shows the percentage with respect to total commercial fuels

[^] The number in the bracket shows the percentage with respect to total fuels

Source: Planning Commission (2008)

3.1 Future Energy Scenario – Baseline versus Low carbon

The two scenarios presented here are *baseline* (no specific policies to reduce demand; coincides with the 'reference scenario' of IEA), and *low carbon future* (efficiency improvements, fuel switching, innovative financing for infrastructure development, implementation of energy policies of the government, etc., coincides with the APS i.e. alternative policy scenario of IEA). Table 2 gives the projected energy demand met through different carriers and CO₂ emissions thereof for these scenarios. In the baseline scenario the coal will progressively increase its share in total demand from 38.7% in 2005 to 47.7% in 2030. Oil and natural gas also follow their respective trend. The demand for other renewables (biomass, hydro, etc.) is likely to be relatively flat. In the low carbon scenario, nuclear, hydro, biomass and other renewables increase their share in the total energy demand. Among fossil fuels, coal loses its share by almost 10 percentage points. Natural gas increases its share being the cleanest fossil fuel. Oil tends to maintain its share because of lack of alternative to oil as transportation fuel. Both nuclear and hydro record increased share under low carbon scenario, however their use is limited because of the socio-environmental concern surrounding nuclear waste disposal and displacement due to large dams. The increase share in biomass and waste in low carbon scenario suggests increased production of bio-power and energy from industrial and municipal waste (IEA, 2007).

Table 2 also gives savings under low carbon scenario vis-à-vis baseline. In 2030, the annual energy saving turns out to be 207 MTOE i.e. one-sixth of the total energy demand. It is worth noting here that reduction in the low carbon scenario does not mean cut down on energy services, rather it indicates fuel substitution and efficient use of fuel. The monetary benefit can be from both the saving through energy bill and Certified Emission Reductions (CERs) obtained for 900 Mt CO₂ emission reduction, which together can be Rs 3.15 Trillion in 2030.^{4,5}

Table 2. Energy demand, and CO₂ emission under Baseline and Low carbon scenarios

Source	2005	Baseline Scenario		Low carbon Scenario		Saving	
		2020	2030	2020	2030	2020	2030
Total primary energy demand (MTOE)							
Coal	208 (38.7)	427 (45.1)	620 (47.7)	330 (39.3)	411 (38.0)	97	209
Oil	129 (24.0)	235 (24.8)	328 (25.3)	206 (24.5)	272 (25.1)	29	56
Gas	29 (5.4)	63 (6.7)	93 (7.2)	61 (7.3)	89 (8.2)	2	4
Nuclear	5 (0.9)	22 (2.3)	33 (2.5)	28 (3.3)	47 (4.3)	-7	-14
Hydro	9 (1.7)	16 (1.7)	22 (1.7)	22 (2.6)	32 (3.0)	-6	-10
Biomass and waste	158 (29.4)	179 (18.9)	194 (14.9)	182 (21.7)	211 (19.5)	-4	-17
Other renewables	1 (0.2)	6 (0.6)	9 (0.7)	11 (1.3)	21 (1.9)	-5	-12
TOTAL	537	946	1299	840	1082	106	217
CO ₂ emissions (Mt)							
Coal	774 (67.5)	1579 (68.4)	2284 (68.9)	1227 (65.4)	1544 (63.9)	351	740
Oil	312 (27.2)	593 (25.7)	829 (25.0)	517 (27.6)	678 (28.1)	76	151
Gas	62 (5.4)	136 (5.9)	201 (6.1)	132 (7.0)	193 (8.0)	4	8
TOTAL	1147	2307	3314	1876	2415	431	899

Source: IEA (2007); [Note: number in parenthesis gives the share in the total]

⁴ As per United Nations Framework Convention on Climate Change (UNFCCC, 1992), India can implement Clean Development Mechanism (CDM) and generate CERs which can be credited to her emission target.

⁵ The assumption for monetary equivalence of 1 unit (1KWh) energy is 1 Re and 1 t CO₂ is 700 Rs.

3.2 Energy for “high humane” Scenario

This scenario presents the case of energy universalization for residential sector. In a recent work Reddy et al. (2009) has developed a scheme for provision of modern energy services (gaseous fuels for cooking and electricity for lighting) to all Indian households by 2030 (Table 3). The regions where there is no access to LPG and electricity, the services are provided through renewable energy technologies (RETs) such as biogas for cooking, and electricity generated through micro-hydro, solar PV or biomass combustion/gasifier for lighting. For the regions, where modern services available, the proposed scheme followed a judicious mix of the centralized and decentralized options.

The incremental annual energy requirements for universalization of household cooking and lighting services are given in Table 4. The CO₂ emission reduction shows the additional emission in case of no universalization program. The reduction is expected to increase during the plan periods and reaching a peak of 158.5mt by 2025-26 and subsequently declining as the targets become closer. Cumulatively, the CO₂ reduction potential of this programme is approximately 2,300mt in the coming two decades. Again, in terms of CER saving, this is equivalent to cumulative saving of Rs 1.61 Trillion by 2030.

Table 3. Energy Universalization Schedule

Table 3: Energy Universalization Schedule						
Year	Rural		Urban		Annual energy requirement	
	Target for provision of services (percent)				Cooking (PJ)	Lighting (GWh)
	Cooking	Lighting	Cooking	Lighting		
2010-11 to 2015-16	35	80	85	100	237	1411
2015-16 to 2020-21	60	90	95	100	310	1426
2020-21 to 2025-26	90	100	100	100	383	1580
2025-26 to 2030-31	100	100	100	100	205	1442
Share of LPG and biogas for the households					Annual emissions (mt)	
	LPG	Biogas	LPG*	Biogas		
2010-11 to 2015-16	50	50	90	10	94	0.09
2015-16 to 2020-21	40	60	85	15	126	0.09
2020-21 to 2030-31	30	70	85	15	238	0.15
Share of Centralized and options for the households						
	Centralized [^]	Decentralized [#]	Centralized	Decentralized		
2010-11 to 2030-31	90	10	100	0		

* LPG for urban area is indicative here, there can be other modern cooking gas services like piped natural gas (PNG).

[^] Centralized power corresponds to conventional electricity based on thermal, hydro and nuclear.

[#] Decentralized power corresponds to electricity obtained from biomass, solar, wind and micro-hydro.

Source: Reddy et al. (2009)

4. ENERGY INFRASTRUCTURE AND INVESTMENT NEEDS

4.1 Capacity Development and Import Needs

The total demand and domestic production of different fossil fuels and electricity generation in the low carbon scenario is presented in Table 4. The difference gives the import. The coal production is likely to increase by 70% in 2030 over its level in 2005,

mainly driven by the power demand. The total production capacity of oil in 2006 is 0.81 million barrels per day. By 2030, the production capacity progressively declines by one-third in 2030 due to relatively low R/P ratio for oil. The high oil demand is going to be satisfied with imports. Hence, from infrastructure point of view, the development of rapid mass transit system (RPTS) has to be high on agenda. The fuel mix in transportation is on account of ethanol and biodiesel blending in petrol and diesel respectively. Natural gas share increases from 5% in 2005 to 8% in 2030 in low carbon scenario on account higher use in power generation. For this the production, transmission and distribution networks will have to be considerably expanded. By 2030, natural gas production will increase by 70% from its level in 2005, whereas the import increases manifold during the same period with a compound annual growth rate of 9.3%. The gross electricity generation in India is at 700TWh in 2005, which will reach 2305TWh by the year 2030, an increase of nearly 3.3 folds (IEA, 2007).

Table 4. Energy Demand and Production in Low Carbon scenario

Production	Unit	2005*			2020			2030		
		T	P	I	T	P	I	T	P	I
Coal	Mt	298	262	36	473	366	107	590	443	147
Oil	(mb/d)	2.71	0.81	1.9	4.10	0.70	3.4	5.44	0.54	4.9
Gas	BCM	35.3	29.3	6	73.3	46.6	27	105.7	49.7	56
Electricity generation	TWh			699			1582			2305

T=Total demand, P=Production capacity, I=Imports, *For oil the values are given for year 2006.

4.2 Investment

Table 5 gives the investment needs in low carbon scenario under different heads for the period of 2010-2030. The investment for coal is Rs 1588 billion which includes mining and port development, with former having almost 95% share.⁶ In mining, there needs to be a tradeoff between opencast and underground types of mining as the former more productive yet is damaging to environment and leads to displacement of villages at times. In low carbon scenario the investment in coal is less by 35% compared to baseline. This is primarily because of pro-policies for renewable energy and nuclear power. The low carbon scenario requires total energy infrastructure investments amounting to Rs 50.3 trillion in the period 2010-2030. This investment is 6.25% less than corresponding figure under baseline scenario. In fact, the supply side investment is 10.56% less in low carbon scenario; however the same has been offset due to increase in demand side investment to improve efficiency of utilization, which amounts 4.5% of investments.

Table 6. Investments needs (Rs billion) in Low Carbon Scenario for the period 2010-2030

Type/Heads	Mining	Exploration and development	Refinery	Generation	Transmission and distribution	Liquefaction	Port development	Total*
Coal	1505 (94.8)						83 (5.2)	1588 (3.2)
Oil		1526 (22.0)	5410(78.0)					6936 (13.8)
Natural gas		1369 (51.0)			1060(39.5)	255(9.5)		2684 (5.4)
Electricity				19454 (53.2)	17135 (46.8)			36589 (73.0)
Demand side								2319 (4.6)
Total								50116

⁶ The investments in thermal based power generation are included under electricity head.

* The values in parenthesis for this column give the share of investment of each type; the values in parenthesis for other columns give the share of investment of each head for a particular type.

5. ENERGY INFRASTRUCTURE POLICY STRATEGIES

The energy infrastructure sector has been characterized by large economies of scale which has resulted in huge investment requirements, particularly in large capacity required in fossil fuels and electric power sector. The funding of such a large lumpy investment has become a major problem for many developing countries including India. The “failure” of the public institutions has made the multilateral institutions such as World Bank to believe that the energy sector needed to be reformed to attract large scale private capital.

5.1 Reducing inefficiencies in Energy Chain

5.1.1 Generation and Transmission

The core of the energy infrastructure issues lies with the inadequacies leading to inefficient generation, transmission and utilization of energy. The coal fired power plants is an example in this regard. The average thermal efficiency of coal fired power plants in India is 27%, whereas for OECD countries it is 37%. Effort to remove the efficiency gap would relax the supply constraint to a great extent. Investment in infrastructure related to plant modernization and developing world class infrastructure for new plants can only give the due value the fuels deserve.

5.1.2 Energy End Use

The inefficiency in the utilization refers to the conversion inefficiency of final energy to useful energy.⁷ Though these inefficiencies are associated with the devices and equipments, in most of the cases poor infrastructure turns out to be the root cause. In India, a relatively large share of industrial output comes from small-scale operations, often located in inner-city slums. Slums not only suffer from civic infrastructure issues like roads, water and electricity, but also house industries which use inefficient technologies and practices breaching environmental norms. In a recent study on Indian manufacturing sector, Ray (2009) concludes infrastructural solutions to energy inefficiencies in cement and paper industry. Similar instance of misuse of energy occur when a high-end energy like electricity is used for low-end purpose like water heating. One kg of coal available in nature loses 87.2% of its energy as it goes through various process of transformation to reach as electricity to the consumers. So energy efficient end use, we need to have policies for demotion of geysers and promotion of solar water heaters in domestic and commercial sector.

5.1.3 The Final Connection

One of the failures in energy infrastructure management in India has been the ‘final connection’. The typical characteristics of any energy infrastructure program results in lower energy bills for future at the expense of higher initial funding, which act as bottleneck to full realization of the potential. Rural electrification program is a case in point. The whole effort to make electricity available to rural households goes in vain as the final electricity connection to the household is not provided. This forces the rural households to rely on inefficient fuel like kerosene for lighting, which in turn defeats the subsidization purpose of kerosene (Mishra et al. 2005). Kerosene is subsidized as cooking fuel, but finally used as lighting and adulterate petrol; and households continue

⁷ Useful Energy (UE) is the portion of Final Energy (FE) which after being converted in energy device is actually available for any use. The useful energy is calculated by taking the efficiency of utilization of the energy device like cooking stove or an electric appliance.

dependency on fuel wood and dung cake (Gangopadhyay. et al. 2005, NACER, 2005). Adulterate petrol adds to the air pollution.

5.2 Role of Actors

There is a growing recognition that the usual investment decisions such as payback period, rate of return on investment, net present value, etc, do not account adequately in infrastructure financing. In the emerging energy markets, there are many actors such as the utilities, state agencies, financial institutions, consumers, market institutions, international organizations, etc. who play important roles. These can be classified broadly into, 'meta', 'macro', meso, and 'micro' levels. At the "meta" level are the international financial institutions which provide financial as well information inputs. At the macro level there are 'high-level' institutions (state/market/civil society) that determine the setting under which the lower levels have to operate (financial, information, training, support by specialists, etc). At the meso level, there are organizations such as energy development agencies (EDAs), energy service companies (ESCs), private entrepreneurs, etc. At the micro level, organizations such as individuals (through domestic savings) operate. Institutions at each level carry out a project at its own level and work within existing 'external constraints' given by 'higher-level' institutions. Fig.1 outlines the roles of actors at different level in promoting energy infrastructure for universal access and low carbon future.

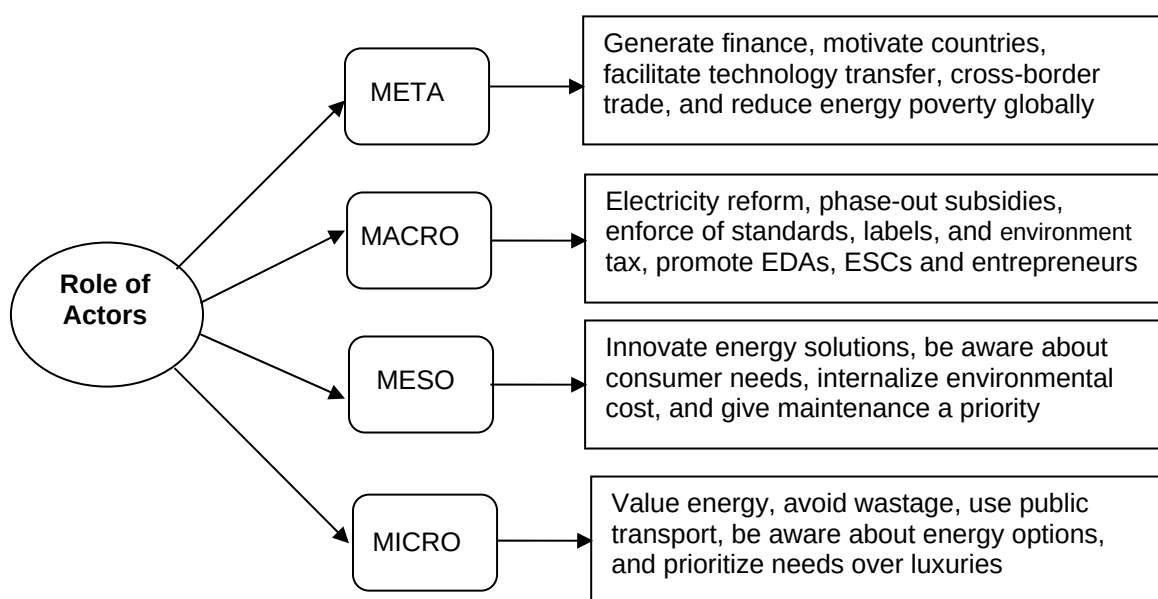


Fig 1. Role of actors

5. 3 Financing Mechanisms

5.3.1 Public vs. Private

For many years energy infrastructure was funded almost exclusively by the public sector. Presently, there is an increasing involvement of cooperative arrangements between governments, multilateral institutions and private investors. Such an approach to succeed a systemic competitiveness is essential. Public-private partnerships (PPPs) are flexible, and are project specific tailor-made solutions. Environmental Finance Programmes (EFP) are also like the Public Private Partnership model, which provides creative approaches to funding infrastructure projects that benefit environmental activities. Environmental Strategy and Policy underscore the positive linkages between the environment and sustainable development. These linkages often involve not just

commodity and resources markets, but also financial markets and innovative sources of finance. Two key linkages are “carbon finance” and the Global Environment Facility. These linkages operate not just to increase financial flows but also to stimulate innovation in the use of natural resources (Peszko and Zylicz, 1998). Investment in energy efficiency (EE) is hard to track in its entirety as efficiency improvements can be done at different levels – generation, transmission and distribution (T&D) and end use devices. Investments come into EE projects particularly to smart/grid distribution and power storage and also in the establishment of energy service companies (ESCOs) and also through Clean Development Mechanisms (CDM).

5.3.2 Financing for Universalisation of Modern Energy Services

Micro financing for projects for Universalisation of Modern energy services through energy efficiency and renewable energy technology is less risky. For example, small-scale water power, or micro-hydro (with capacity less than 100kW), can be a particularly attractive option for electrification in many rural areas. Three major factors contribute to the success of such projects: (i) participation of the beneficiaries in project planning and implementation, (ii) development of a local manufacturing base to produce low-cost equipment, (iii) capacity building at the community level to enable the replication of the technology.

6. CONCLUSIONS

Investment in energy infrastructure is the need of the hour to save climate and reduce poverty. This investment will expand energy supply capacity and replace the existing and future supply facilities that will be exhausted or become obsolete in near future. The total investment is around Rs 50 trillion for the next two decades. This investment is required to expand the supply capacity and to replace existing and future supply facilities that will be exhausted or become obsolete during this period. The issues to be considered while discussing financing for energy infrastructure are (i) safeguarding debt sustainability of the country; (ii) need to manage socio-environmental impacts (iii) the ability to provide energy services and achieve the Million Development Goals (MDGs); (iv) the importance of regional integration in the promotion of cross-border trade; (v) the need to mainstream energy policies into national development strategies and address the issues of inadequate budget allocations to the energy sector; and (vi) the need for a comprehensive approach to the building of human capital. Unless these issues are addressed in an integrated and effective way the prevailing inadequacies are expected to continue even in the future.

Energy infrastructure is the key to meet the challenge of energy universalization and climate change mitigation. Infrastructure can be sustained to remain effective if the leaks in the energy system are identified and minimized. All the stakeholders in the system, the government, international institutions, industries, business associations, civil society, and consumers have responsibility in this regard. A high humane and low carbon energy infrastructure satisfies the three principal goals of energy policy: improved economic efficiency, more environmental protection, and greater security.

REFERENCES

- CEA (Central Electricity Authority), 2008, *Annual Report: 2007-08*, CEA, Ministry of Power, Government of India, New Delhi
- EU (European Union), 2008, *Information Reference Document, EU Climate Change Expert Group 'EG Science'*, July.
- Gangopadhyay S, B. Ramaswami and W. Wadhwa, 2005, “Reducing subsidies on household fuels in India: how will it affect the poor?” *Energy Policy*, Vol. 33, No. 18, pp. 2326–2336.

IEA (International Energy Agency), 2007, *World energy outlook 2007, China and India Insights*. Paris: OECD/IEA.

IEA (International Energy Agency), 2008, *World energy outlook 2008*, OECD/IEA, Paris.

Misra, N., R. Chawla, L. Srivastava and R. K. Pachauri, 2005. *Petroleum prices in India: balancing efficiency and equity*. New Delhi: TERI Press.

NACER (National Council of Applied Economic Research), 2005, *Comprehensiv Study to Assess the Genuine Demand and Requirement of SKO*, NACER, New Delhi.

NSSO (National Sample Survey Organization) 2007, *Energy Used by Indian Households 2004/2005*, NSS 61st round. Ministry of Statistics and Program Implementation, Government of India

Peszko G. and T. Zylitz, 1998, "Environmental financing in European economies in transition", *Environmental and Resource Economics*, Vol. 11, No. 3-4, pp. 521–553.

Planning Commission, 2006. "Integrated Energy Policy: Report of the Expert Committee." Planning Commission, Government of India.

Planning Commission, 2008. *Eleventh Five-Year Plan, 2007-12, Agriculture, Rural Development, Industry, Services and Physical Infrastructure, Volume III*. Planning Commission, Government of India

Ray B. K., 2009, *Energy Efficiency and Technology Management in Indian Industry*, PhD Dissertation, Indira Gandhi Institute of Development Research, Mumbai, December, 2009.

Reddy, Sudhakar B. and Gaudenz B. Assenza. 2009. "Climate Change: a developing country perspective". *Current Science*, vol. 97, no. 1, pp. 50-62, Jul. 2009

Reddy Sudhakara B, P. Balachandra and Hippu Salk Kristle Nathan, "An entrepreneurship model for energy empowerment of Indian households – Economic and policy analysis", Article in Press, *Energy Policy*, Vol 37, No 11, November 2009, pp 4645-4657.

UNDP (United Nations Development Programme). 2009, *Human Development Report, 2009*, Overcoming barriers: Human mobility and development, Oxford University Press, New York.

UNFCCC (United Nations Framework Convention on Climate Change), 1992, *Text of the convention of climate change*, UNFCCC.

SESSION 1.3

MODELLING CHANGES IN THE METABOLISM OF SOCIETIES

Schramski J. R., Rutz Z. J., Gattie D. K., Li K.

MODELLING A TROPHICALLY BALANCED ECONOMY

Némoz S.

THE MEANING OF REBOUND EFFECTS IN THE ENERGY-RELATED PRACTICES OF HOUSEHOLDS

Iorgulescu R. I., Albu L. L., Stanica C., Polimeni J. M.

ROMANIAN METABOLISM AND SUSTAINABLE POLICIES (MUSIASSEM AT LEVEL N-4)

Karakatsanis G.

MODELLING THE ENERGY DYNAMICS OF HUMAN CIVILIZATIONS WITHIN THE THEORY OF CULTURAL EVOLUTIONISM

Luzzati T. and Orsini M.

A ROBUSTNESS EXERCISE ON THE EKC FOR CO₂ EMISSIONS

Dogaru V.

PROPOSAL FOR AN ANALYTICAL SIMILE FOR INTRA-EUROPEAN EXCHANGE OF MATTER-ENERGY. MANOILESCU – GEORGESCU-ROEGEN MODEL

MODELLING A TROPHICALLY BALANCED ECONOMY

J.R. Schramski¹, Z.J. Rutz², D.K. Gattie³, K. Li¹

¹ *University of Georgia, Faculty of Engineering, Athens, GA USA*

² *Duke University, Pratt School of Engineering, Durham, NC USA*

³ *University of Georgia, Biological and Agricultural Engineering, Athens, GA USA*

ABSTRACT

Considering an economy without fossil fuels, literally built from the ground, then up, we developed several interactive research models of biointensive farms that use no fossil fuels. Quantifying and summarizing total human labor-energy input and total caloric energy output, we demonstrate that a successfully designed farm can produce a positive energy-return-on-investment (EROI) leaving additional labor-energy ostensibly for building extra economic-community structures such as schools and hospitals. Farm products with negative EROI must be coupled with other products with positive EROI to assure nutritionally balanced diets are maintained while still achieving an overall positive EROI for the total agroecological operation. We show that similar to the ecosystem, energy budgets are tight which makes for difficult decisions on diet, farm plot diversity, and energy profitability for future economic growth. Considering the totality of this low energy agro-system based economy, we simplify many operational variables into a unique graphical solution space which reveals both reasonable expectations of agroecological EROI performance and extreme asymptotes beyond which indicate regions of system failure.

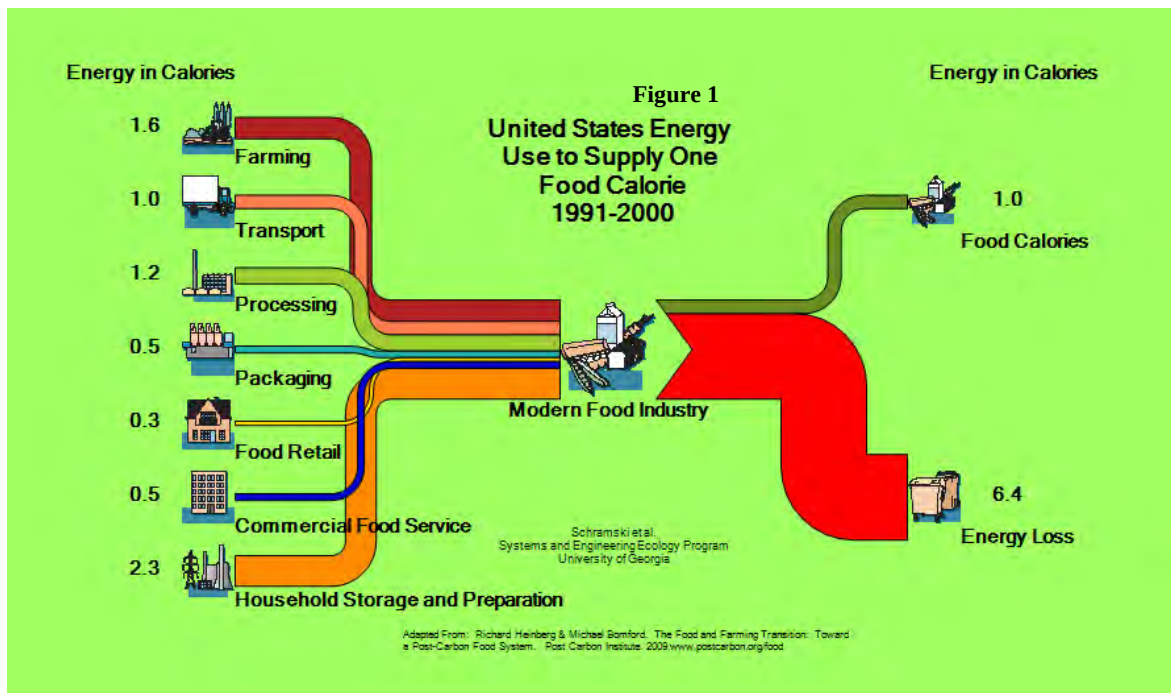
Keywords: energy, agroecology, sustainable agriculture, EROI

1. INTRODUCTION

As energy supplies dwindle or the ramifications of fossil fuel consumption become better understood, efforts to reduce overall energy consumption are a looming priority in a variety of sectors of the U.S. economy. In particular, the U.S. food supply system is a large energy consumer and therefore at the center of this issue. As illustrated in Figure 1, for every Calorie of food produced, approximately seven Calories of energy are consumed by the extended agricultural supply system. (We use the standard convention where one food Calorie equals 1,000 chemist calories or 1kcal where the former is capitalized and the later is not. This research deals exclusively with food Calories.) Although a wide range of public and private resources are developing to both understand and reduce nonrenewable energy consumption (examples include: DOE's Energy Efficiency and Renewable Energy Program and their Alternative Fuels Program, the Bioenergy Feedstock Information Network (BFIN), and the university based Sun Grant Initiative, etc.), the initiation of energy studies specifically for agriculture has been considerably smaller, and noticeably yet more limited within sustainable agriculture. Biofuels are one exception and an area of intense research; however, agriculture intensive energy research is primarily dominated by renewable energy research that is secondarily applied to agricultural systems. For example, the USDA's Sustainable Agriculture Research and Education (SARE) organization's 2006 workshop was organized to "bring together various groups and agencies that focus on renewable energy and sustainable agriculture to exchange information and identify areas of commonality." Yet, the concluding summary of

* Corresponding author; E-mail: jschrams@uga.edu; Tel: (706) 542-4828

potential topics for research almost exclusively referenced plant-based fuel areas (a.k.a., biofuels) ostensibly to aid farm operations or simply for farm production and sale. The summary did identify, however, that an increase in energy conservation needs to be added to future discussions.



A comprehensive systems approach with a long-term sustained effort towards the understanding of energy in agriculture is needed where organic farming currently recognizes the use of mechanical cultivation and generally embraces energy conservation only indirectly by promoting the reduction of climate change practices (e.g., The Rodale Institute). No policies, goals, or plans are in place to address renewable or nonrenewable energy in sustainable agriculture. As such, we jump ahead of the current issue and theoretically consider an organic operation without fossil fuels to begin engineering the foundation for future considerations and to also identify technology and insight that can be appropriately inserted into current circumstances.

2. MATERIAL AND METHODS

The theoretical numerical model simulates a biodynamic French intensive style farm located in the Georgia piedmont, USA. Jeavons (2001a, 2001b, 2001c, 2001d, 2001e, 2006) further developed and documented this methodology over the last 40 years into the sustainable mini-farming practice of GROW BIOINTENSIVE® (GB). Organic farming techniques are similar such that to minimize pests (e.g., weeds, insects, etc.) and improve sustainability (e.g., promote genetic diversity, use little to no fertilizers, etc.) the varying methods generally focus on both soil and plant development with continuous knowledge enhancement applied to specific (local) conditions. Given the immense biological complexity associated with geographic diversity, organic methods respect and promote the deep knowledge development necessary for local community based efforts.

In general, according to GB research, a sustainable operation including the perpetual maintenance of supporting soils, can be developed and eventually fine-tuned to a reasonable level of sustainability if the overall mini-farm maintains an approximate 60% grain-seed, 30% root, and 10% vegetable product distribution ratio (a.k.a., 60/30/10). The grain-seed crops (carbon-and-calorie crops) generate large amounts of carbon for compost and high calorie foods and are weight-efficient. The root crops produce high

calorie foods and can be area- and or weight-efficient. The vegetables are low calorie, low carbon, and produce vitamins and minerals as needed to complete a sufficient diet. Weight-efficient crops require 9 pounds or less to meet daily caloric requirements. Area-efficient crops require 16 beds or less at medium yields to meet an annual caloric requirement. In the GB system, 1 bed is 100ft². Annually, approximately 40 beds (4,000 ft²) are required per person to run the 60/30/10 system. This is roughly 5,000 ft² including paths.

Vitamin B₁₂ is not available in a purely plant based diet. A large structurally complicated vitamin, it is artificially produced only by a bacterial fermentation process. Reasonably assuming this process is not available for a small farm operation, animal products were added to the theoretical GB farm operation algorithm. Although a variety of animal products supply B₁₂, for simplicity, we used eggs. For our model, we assume a moderate production of 300 eggs produced per year per chicken for the GA piedmont.

We constructed an interactive computational model that quantified farm nutritional and caloric energy output by referencing both the USDA's recommended nutritional guidelines (USDA 2009) database and Jeavons' (2006) yield data. Table 1 lists the GA piedmont capable mix of grain, root, and vegetable farm products selected from Jeavons' tables included in the model's possible selections.

Table 1. Medium and high yield crops in Calories/bed/day (Jeavons 2006)

Grain & Seed			Root			Vegetable		
	Medium	High		Medium	High		Medium	High
Wheat	41	99	Potatoes	191	746	Peanuts	70	169
Cereal Rye	42	100	Garlic	222	444	Soybeans	41	72
Oats	34	63	Jerusalem	195	435	Kidney	41	99
			Artichoke			Beans		
Barley	43	104	Leeks	364	729	Burdock	134	269
Corn	77	104	Parsnips	222	446	Cassava	119	239
Sorghum	67	101	Sweet Potatoes	180	539	Onions	94	254
Filberts	118	236	Salsify	204	408	Turnips	68	123
Amaranth	76	152				Rutabaga	179	357
Quinoa	57	114				Tomatoes	50	109
Fava Beans	13	25						
Sunflower	35	71						
Seeds								

The theoretical 4,000ft² farm plot is divided into forty 100 ft² beds such that the grain, root, and vegetable crops are divided into 24, 12, and 4 possible beds respectively to meet the 60/30/10 GB division goal for reasonable soil quality and production sustainability. The model algorithm allows an interactive selection from the lists of grain, root, and vegetable crops with the constraint that the final number of beds in each category shall meet the 24/12/4 division requirement. The model also allows a quantity selection of egg laying hens primarily to supplant the B-12 vitamin deficiency of a plant only diet. However, all nutrients associated with these eggs are added to the overall results. On average, high yields are about 2.5 times greater than medium yields in Jeavons' data. As such, considering our egg addition we used 10 laying hens for our medium and 25 laying hens for our high yield operations. These were chosen to represent a reasonable number that can be sustained in a very small farm operation without overworking their feeding territory (one half acre or less). Accessing the USDA nutritional capacity of each product, the model calculates the combined nutritional quality of the overall selection. The modeler then interactively adjusts their selections until a balanced nutritional diet is achieved coupled with a 24/12/4 farm plot division.

Table 2 and Figure 2 show several successful whole system farm selections. For example, Farm 1 is a medium yield, reasonably diverse farm capable of feeding 1.65 people with sodium as the limiting nutrient. In other words, although this farm provides greater than 165% of the remaining USDA's recommended vitamin and mineral quantities,

this farm produces exactly 165% of the USDA's annual sodium requirement. Thus, in total this farm can only support 1.65 individuals. The model also computes the farm's Caloric energy output and then compares it to a generally accepted per capita required Caloric input. Daily per capita Calorie input requirements vary considerably with age, weight, physical conditioning, gender, etc. (Leslie et. al 1984, WHO 1985, FAO/WHO/UNU 2001, Babatunde et. al 2010). As a consistent assumption, we use the commonly referenced WHO published average of 2,500 Calories per day to sustain each person (WHO 1985, FAO/WHO/UNU 2001).

As a demonstrative example, consider the sodium limited medium yield Farm 1 shown as a solid circle data marker on Figure 2. If sufficient sodium supplement were artificially added from an external source, Caloric energy output happens to become the next limiting commodity for this farm configuration. The modified medium yield Farm 1 then supports 2.20 people as indicated by the solid square data marker. In other words, although this farm provides greater than 220% of the remaining USDA's recommended vitamin and mineral quantities (except sodium), this farm produces exactly 220% of the WHO recommended per capita energy intake. Thus, in total a sufficiently sodium supplemented medium yield Farm 1 could support 2.2 individuals. As shown with the open circle data marker in Figure 2, if high yield outputs from Table 1 are substituted for the same Farm 1 products and bed quantities with (no sodium supplements), the total energy output rises to 11,496 Cal with sodium remaining the limiting commodity (3.72 individuals supported). Through variation of the farm products and their respective bed quantities, similar to the examples expressed from Farm 1, the computational model generates diverse combinations of practical system solutions for the 4,000 ft² operation each with sufficient nutritional and caloric output.

3. RESULTS

Considering the range of farm system solutions as they pertain to varying inputs and outputs, we specifically explore limiting factors to improve our understanding of sustainable agriculture's capacity and limitations, particularly as the system responses affect energy outputs. The objective is to identify and quantify respective boundary limits with regard to, for example, harvest diversity, total caloric output, and farm efficiency. Farm efficiency is defined here as the number of individuals supported by the farm (accounting for both Caloric and nutritional output) per an assumed one farmer's manual input to the 4,000 ft² operation.

Figure 2 depicts a potential solution space for all complete diet (100% or greater of the USDA's recommended supply of vitamins and minerals) combinations of the Table 1 farm product choices (e.g., wheat, barley, oats) and their quantities (number of beds and their yields). As a relative boundary, the solid ascending-positive sloped line represents the FAO minimum 2,500 Calorie diet per individual supported by the farm output (FAO/WHO/UNU 2001). Assuming all farms plotted on this graph supply a complete diet, Caloric energy limited farms operate below-right of this line, and Caloric energy sufficient farms, operate above-left of this line. If the intent is to support two individuals with this farm, then the output should not be below 5,000 Calories, and so on.

Two energy yield boundaries for the 40 bed operation are indicated (Figure 2). The lower and upper dashed lines represent medium and high-energy yield harvest operations, respectively. In total, 10 farms were used to construct the high yield and 16 farms were used to construct the medium yield trend lines. Sustainable agriculture is an extensive learning and developmental process for each piece of land cultivated. For example, Jeavons refers to beginning, intermediate, and fully experienced food growers in the GB method where a fully experienced food grower is the result of over 10 years of farming and corresponding learning (thus generating high yields). Soil quality and soil capability or various plant diversity schemes to maximize yields and seed production while minimizing disease, harmful insects, and weeds are only some of the important aspects of food production to be meticulously engineered over sequential seasons. Medium yields

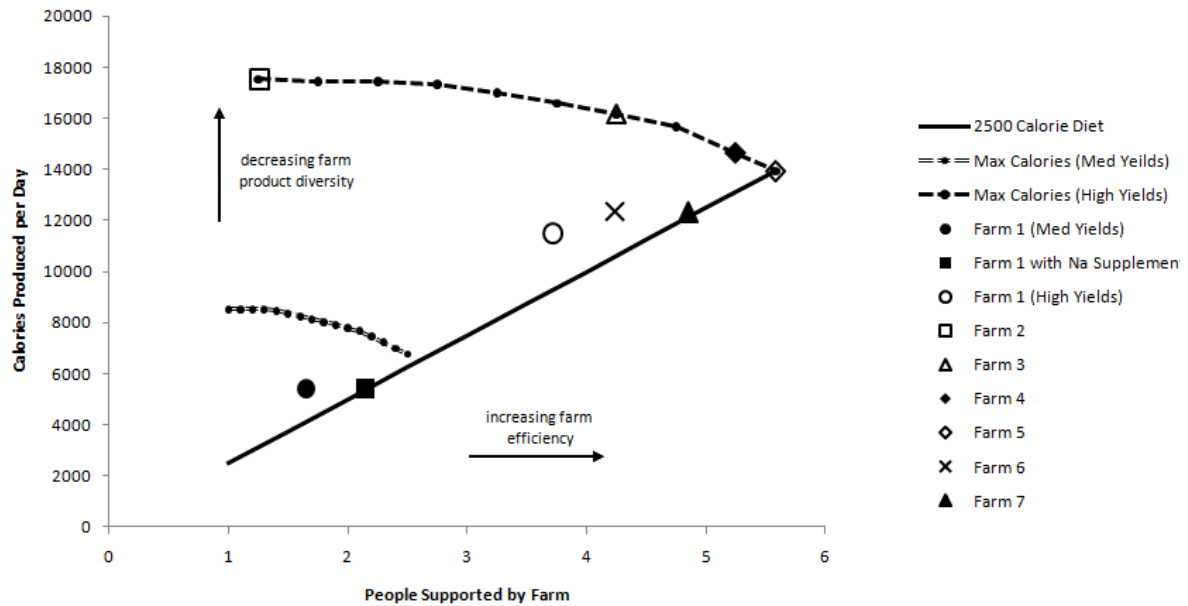


Figure 2. Theoretically possible Caloric outputs of a 4,000 ft² fossil-fuel-free Grow Biointensive® 60/30/10 farm supplemented with egg laying hens located in the Georgia piedmont, USA, manually farmed by one individual. All farms shown have 40 beds and provide 100% or more of the U.S.D.A. recommended vitamins and minerals.

represent the beginning stage for a farm and farmer somewhere short of the fully experienced stage of development. The distance between these two lines in the solution space of Figure 2 illuminates the importance of farmer skills, soils development, and a total system approach, with regard to annual farm efficiency. The location of the high-energy yield line also represents a boundary or asymptote of maximum energy output for the 4,000 ft² space.

Microsoft Solver (MS) [which uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code (Lasdon et al. 1978, Lasdon and Smith 1992)] was used to optimize the farms' medium and high-energy yield energy output configurations shown with the lower and upper dashed lines in Figure 2. We forced the MS algorithm to maintain a 100% or greater USDA recommended level of vitamin and minerals with all configurations. Within this overriding constraint, the MS optimization routine was allowed to vary both the Table 1 farm products and their quantity of beds while maintaining the GB 24/12/4 farm plot division (40 beds total required) to optimize and ultimately generate the farm configurations for various maximum energy outputs. Farm 2, shown in Table 2, represents the maximum output energy possible at 17,531 Cal for the farm products listed in Table 1 organized in the 24/12/4 configuration requiring 40 beds total and will support 1.26 people with vitamin A being the limiting factor. This is the least diverse farm configuration (Shannon diversity of 0.9) requiring only 3 crops (filberts, potatoes, and rutabagas) of the maximum number of beds (24, 12, and 4) and the maximum egg laying hens (25) to meet all of the USDA nutritional requirements. Farm configurations which continue to maximize Caloric output but supporting fewer people would be possible but would require less than 40 beds. Therefore, Farm 2 represents the optimum configuration to support the largest energy output and viable farm on the 40 bed high-energy yield line. Farms 3, 4, and 5 in Table 2 are three of the nine additional farms that were used to create the high yield energy line. As the number of people supported by the farm is increased within the optimization algorithm parameters, the result is that the farm product diversity increases (due to the increased nutrient and mineral requirements for more individuals) and thus the total Caloric output is reduced causing the high yield energy line

Table 2. Farm options shown in Figure 2.

	Farm 1			Farm 2		Farm 3		Farm 4		Farm 5		Farm 6		Farm 7	
	MY*	HY*													
	Beds	Cal	Cal	Beds	Cal	Beds	Cal	Beds	Cal	Beds	Cal	Beds	Cal	Beds	Cal
Grain/Seed															
Filberts	4	472	946	24	5,673	24	5,673	24	5,673	24	5,673	10	2,364	11.6	2,742
Wheat	3	123	296									2	197	0.7	69
Cereal Rye	2	84	200									2	200	0.8	80
Oats	3	102	188									2	126	1	63
Corn	8	616	835									4	417	1.1	115
Barley	2	86	208									2	208	0.8	83
Sorghum	2	134	202									2	202	0.9	91
Amaranth														1.8	273
Quinoa														1.4	160
Fava Beans														0.5	13
Sunflowers														3.4	241
Root															
Potatoes	1	191	746	12	8,950			2.55	1,902	0.58	431	1	746	0.6	447
J. Artichoke	4	780	1,739			3.9	1,697	7.84	3,409	8.72	3,791	5	2,174	6.7	2,913
Leeks	2	728	1,457			8.1	5,899	1.05	765	1.43	1,042	2	1,457	2.2	1,603
Salsify	2	408	815					0.56	228	1.27	519	2	815	0.6	245
Garlic	1	222	444											0.4	178
Sw. Potatoes	1	180	539									1	539	1.1	593
Parsnips	1	222	446									1	446	0.4	178
Vegetable															
Rutabaga	2	358	715	4	1,429	4	1,429	3	1,072	2.5	893	2	715	0.6	214
Kidney Beans								1	99	1.5	149			0.6	60
Soybeans	1	41	72									0.5	36	0.4	29
Peanuts	1	70	169									1	169	0.4	68
Turnips												0.5	62	0.4	49
Burdock														0.4	108
Cassava														0.4	95
Onions														0.4	102
Tomatoes														0.4	44
Totals															
	Farm 1	1-MY*	1-HY*	Farm 2		Farm 3		Farm 4		Farm 5		Farm 6		Farm 7	
Beds	40	40		40		40		40		40		40		40	
Plant Cal.	4,817	10,017		16,052		14,698		13,148		12,498		10,873		10,856	
Hens	10	25		25		25		25		25		25		25	
Egg Cal.	592	1,479		1,479		1,479		1,479		1,479		1,479		1,479	
Total Cal.	5,409	11,496		17,531		16,177		14,627		13,977		12,352		12,335	
People Supported	1.65	3.72		1.26		4.25		5.25		5.59		4.24		4.85	
Limiting Nutrient	Sodium	Sodium		Vitamin A		Sodium		Sodium, Riboflavin		Cal, Sodium, Riboflavin		Sodium		Sodium, Riboflavin	
Shannon's Diversity	2.62	2.62		0.90		1.09		1.24		1.22		2.51		2.61	
Shannon's Equitability	0.93	0.93		0.82		0.78		0.64		0.63		0.89		0.79	

*MY is medium yields, HY is high yields, Farms 2-7 use high yields

to dip as it is plotted to the right on the horizontal axis. In Farm 3, potatoes are swapped with artichokes and leeks subsequently increasing the number of individuals supported to 4.25 (sodium is the limiting quantity) with a total energy output of 16,177 Calories. Farm 4 adds salsify, potatoes, and kidney beans to the overall diversity increasing the number of individuals supported to 5.25 (sodium and riboflavin are both limiters) reducing the total energy output to 14,624 Calories. Similarly, Farm 5 changes the overall quantities of products from Farm 4 to increase the number of people supported to 5.58 with a total energy output reduced to 13,939 Calories. Farm 5's energy output intersects with the solid ascending-positive sloped line which represents the FAO minimum diet of 2,500 Calories per individual. As such, the limiting commodities are now sodium, riboflavin, and energy. Thus, the high yield energy line and the FAO 2,500 per capita Calorie line are upper and lower boundaries, respectively, to the solution space which converge with the Farm 5 commodity and quantity choices representing a potential optimum convergence

point. As quantified with the Shannon diversity coefficient, the farm plot species diversity increases from Farm 2's to Farm 5 product selections.

Although the boundaries to the farm solution space are revealing, boundary farm operations are not reasonable and provide no room for unpredictable events, uncertainties, or errors. The high yield Farm 1 is one example of a reasonable selection within the solution space offering a USDA and energy sufficient diet with some diversity in product selection potentially supporting 3.72 people. Farm 6 was generated by slightly adjusting both the product selection and bed quantities from Farm 1 thus improving farm efficiency to 4.24 but decreasing diversity from 2.62 to 2.51. This represents a useful adjustment within the solution space to increase a targeted parameter, in this case, farm efficiency. When compared to Farm 6, Farm 7 represents an improvement through a forced diversity of at least 40ft² (bed size = 0.4) of all potential products thus decreasing the overall energy output slightly from Farm 6 (12,353 Cal down to 12,335 Cal) but also increasing the farm efficiency from 4.24 to 4.85 people supported and also increasing overall diversity to 2.61 in the diet structure.

DISCUSSION

As natural resources continue to be depleted, sustainable agricultural systems will eventually move towards commodity neutral balances with regard to their adjacent ecosystems (e.g., carbon, nitrogen, water, biota, energy, etc.). The luxury of being able to rely on distal supplies or deposits to accommodate unbalanced local environmental relationships is diminishing. System approaches such as low-input agriculture (House and Brust 1989, Pimentel et al. 1989) or traditional ecological knowledge (TEK) approaches (Martin et al. 2010) will become mainstream practices rather than soft science concepts pursued only by a few. They will comprise the systems tools to comprehensively support a better understood input-output, balanced relationship with local environments to sustain a large-scale food supply network that may be far less centralized. One challenge attributed to this era of agroecology (Jackson 1980; Gliessman 1990, 2006) will be to determine the boundaries of these input-output calculations such that future communities will reconnect with their local habitat in ways not currently envisioned. Essentially, a systems oriented ecologically balanced agriculture is inevitable (Francis and Madden 1993), although the timeline of implementation is unknown.

Predicting the staged implementation of a systems approach to the current agricultural endeavor and then selectively inserting effective, ongoing engineering research, is difficult at best. This model precludes this quandary by addressing an agroecological economy of energy as initiated from one person's harvest with no external energy or material supplies. If the labor of one farmer on an ecologically balanced farm operation can generate sufficient energy, nutrients, and diet diversity to support the existence of more than one individual, then theoretically at some greater scale, the excess labor is available to build and operate a community and associated economy (e.g., hospitals, businesses, schools, etc.). A core building block for a community's relationship with its local environment emerges forcing its anthropocentric sub-sector to operate within its local ecosystem's energetic (eco-trophic) envelope.

A degree of uncertainty is always inherent with ecosystem calculations, particularly energy calculations. Nevertheless, the solution space generated in Figure 2 represents a foundation for future agroecological energy balanced work. Figure 3 highlights a reasonable target region for a community to consider to ostensibly balance harvest diversity, a USDA balanced diet, energy sustainability, and overall farm efficiency.

Considering our approach, if we remove fossil and nuclear fuels from the potential energy solution scheme, agriculture becomes central to community development and to overall anthropocentric energy cycling.

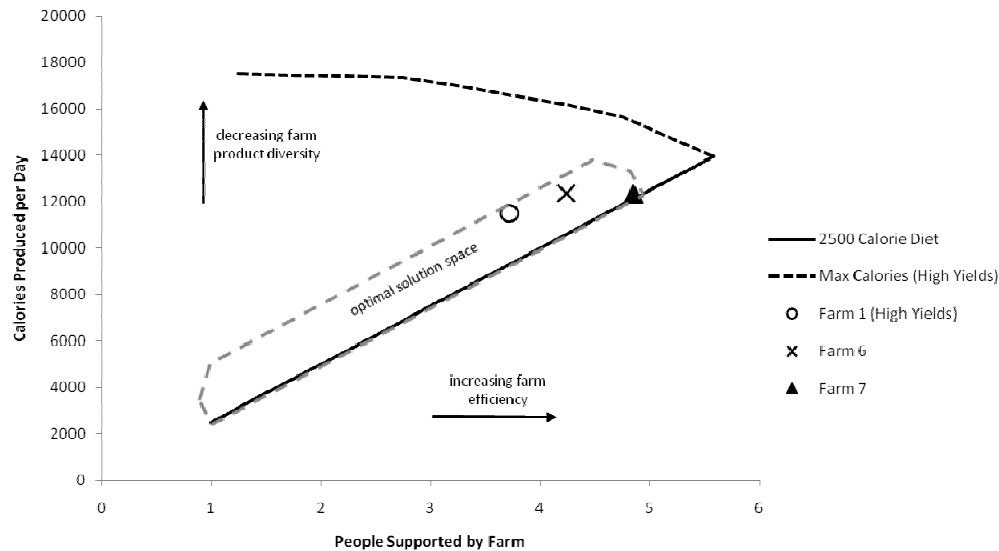


Figure 3. Optimal solution space to balance farm plot diversity, diet balance, energy sustainability, and farm efficiency for a 4,000 ft² 40 bed, fossil-fuel-free Grow Biointensive® 60/30/10 farm supplemented with egg laying hens located in the Georgia piedmont, USA manually farmed by one individual.

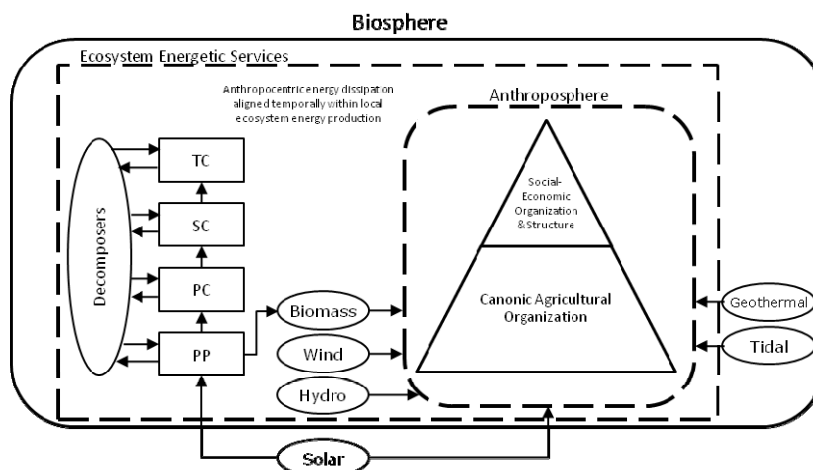


Figure 4. Temporally relevant (without nuclear or fossil fuels) anthropocentric energy sources in the biosphere.

The results demonstrated in Figure 2 with farm efficiencies greater than 1 then become the economic engine in an agroecological economy of Figure 4. Most importantly, the energy-return-on-investment (EROI) of a sustainable operation is positive. As the technologies associated with farm efficiency are improved (EROI increases), more individuals are supported by the agricultural operation to make their labor energies available for the social and economic organization and structure allowing the local economy to grow. Admittedly, by today's standards, these energy margins are extremely small. Yet, if we consider the ecosystem example, a specific species trophic survival depends on successfully finding a niche of continuous energy potential that neither exploits nor extinguishes its local habitat's perpetual ability to maintain that potential. The anthropocentric endeavor will be no different in this fundamental pursuit, but will, however, be exceedingly different in the level of knowledge and information available to establish this agroecological system. This type of perspective forces its anthropocentric sub-sector to operate within its eco-trophic envelope and to most importantly develop ideas, not

apparent in existing energy models, that will also help manage the current situation as our fossil fuel supplies dwindle.

ACKNOWLEDGEMENTS

We would like to personally thank John Jeavons and Ecology Action for a lifetime of work and dedication to generate the information and dataset integral to this research. We would also like to thank Jan Southers of Hope Spring farm and Josh Johnson of UGA's Environmental Engineering program for their essential help in determining the poultry data for our model development. Finally, we would like to thank UGA's Faculty of Engineering and the Systems and Engineering Ecology Program for their ongoing support of our research.

REFERENCES

- Babatunde RO, Adejobi, AO, and Fakayode, SB. 2010. "Income and calorie intake among farming households in rural Nigeria: results of parametric and nonparametric analysis". *Journal of Agricultural Science*. 2, 2:135-146.
- FAO/WHO/UNU. 2001. *Human energy requirements*. Report of a joint FAO/WHO/UNU. FAO food and nutrition technical report series. Rome.
- Francis CA, and Madden JP. 1993. "Designing the future: sustainable agriculture in the US". *Agriculture, Ecosystems & Environment*. 46:(1-4)123-134.
- Gliessman, Stephen R. *Agroecology: Researching the Ecological Basis for Sustainable Agriculture*. New York: Springer-Verlag, 1990. ISBN: 387970282
- Gliessman, Stephen R. *Agroecology: The ecology of sustainable food systems*. 2nd edition. CRC Press. N.Y. 2006. ISBN 0849328454.
- House, GJ, Brust, GE, 1989. "Ecology of low-input, no tillage agroecosystems". *Agriculture, Ecosystems & Environment*, 27:(1-4)331-345.
- Jackson, W., 1980. *New Roots for Agriculture*. Univ. Nebraska Press, Lincoln, Nebraska
- Jeavons, JC. 2001a. "Biointensive sustainable mini-farming: I. The challenge". *Sustainable Agriculture*. 19:(2)49-63.
- Jeavons, JC. 2001b. "Biointensive sustainable mini-farming: II. Perspective, principles, techniques, and history". *Sustainable Agriculture*. 19:(2)65-76.
- Jeavons, JC. 2001c. "Biointensive sustainable mini-farming: III. System performance-initial trials". *Sustainable Agriculture*. 19:(2)77-83.
- Jeavons, JC. 2001d. "Biointensive sustainable mini-farming: IV. System performance-continuing trials in a more difficult environment and soil". *Sustainable Agriculture*. 19:(2)85-97.
- Jeavons, JC. 2001e. "Biointensive sustainable mini-farming: V. Future potential, some representative world applications, future challenges and research opportunities". *Sustainable Agriculture*. 19:(2)99-106.
- Jeavons, J. 2006. *How to Grow More Vegetables*. Ten Speed Press. Berkeley, CA.
- Lasdon, L. S.; Waren, A. D.; Jain, A.; and Ratner, M. 1978, "Design and testing of a generalized reduced gradient code for nonlinear programming," *ACM Transactions on Mathematical Software*, Vol. 4, No. 1, pp. 34-49.
- Lasdon, L. S. and Smith, S. 1992, "Solving large sparse nonlinear programs using GRG," *ORS A Journal on Computing*, Vol. 4, No. 1, pp. 2-15.
- Leslie, PW, Bindon JR, and Baker, PT. 1984. "Caloric Requirements of Human Populations: A Model". *Human Ecology*. 12, 2:137-162.
- Martin, JG, Roy, ED, Diemont, SAW, Ferguson BG. 2010. Traditional Ecological Knowledge (TEK): Ideas, inspiration, and designs for ecological engineering. *Ecological Engineering*, 36:839-849.
- Meinshausen, M, 2007. Climate change and human development – risk and vulnerability in a warming world, *Human Development Report 2007/2008*. Palgrave Macmillan, New York.
- Pimentel, D, Culliney, TW, Buttler, IW, Reinemann, DJ, and Beckman, KB. 1989. "Low-input sustainable agriculture using ecological management practices". *Agriculture, Ecosystems & Environment*. 27, 1-4:3-24.

- Steiner, Rudolf. 1993. *Spiritual Foundations for the Renewal of Agriculture: A Course of Lectures*. Bio-Dynamic Farming and Gardening Association, Kimberton, PA. 310 p.
- U.S. Department of Agriculture, Agricultural Research Service. 2009. *USDA National Nutrient Database for Standard Reference*, Release 22. Nutrient Data Laboratory Home Page, <http://www.ars.usda.gov/nutrientdata>.
- WHO. 1985. *Energy and protein requirements*: Report of a joint FAO/WHO/UNU expert consultation. WHO Technical Report Series No. 724. Geneva.

THE MEANING OF REBOUND EFFECTS IN THE ENERGY-RELATED PRACTICES OF HOUSEHOLDS

*Sophie Némot**

*Centre for Studies on Sustainable Development (CEDD – IGEAT)
Université Libre de Bruxelles (ULB)*

ABSTRACT

In this talk I aim at sharpening a sociological focus on the rebound effects in the metabolic patterns of societies. Nowadays the work to this goal is gaining new momentum. Over the past thirty years, the energy use of appliances has been steadily decreasing with greater awareness of the importance of energy efficiency and innovations in technologies. However, overall household energy consumption for this period has risen. According to several economists, a part of this phenomenon is due to “rebound effects”. The general principle behind the rebound effects is that by reducing a product’s energy consumption, pollution and use of natural resources are also reduced, but less energy use means lower running costs which encourage greater use of the product, limiting the benefits that the energy reduction should have brought. Indeed, the issue of rebound effects raises basic questions about a break in the addiction to fossil energy. Firstly, we will begin by briefly reviewing a range of economic studies on this subject and as we will see, most of them revolve around a strikingly limited understanding of the social world and how it uses energy resources. Inferring from such an assessment, a research was concentrated on revitalizing the discussion, by rethinking the concept of rebound effects through an empirical approach. Its fieldwork is dedicated to the energy-related practices of Belgian households. Through qualitative methods applied to dwelling energy consumption (fuels and electricity) and to everyday mobility (work and leisure), the underlying idea of this sociological study is to determine the structure and some mechanisms of the trend so-called “rebound effects”. This perspective leads to reconsider other possible analyses including those grounded in social theories of practice and transition. Finally, the ambition is not only to gain an insight into the societal meaning of rebound effects but also to help identify opportunities for making better use of existing scientific resources.

Keywords: rebound effects, energy economics, metabolic patterns of societies

1. INTRODUCTION

The current debate on energy consumption has highlighted a variety of tensions between the pursuit of wellbeing and the need to remain within ecological limits. The issue becomes particularly important in the context of a kind of ‘double dividend’ implicit in the idea of efficiency: the possibility that we might ‘live better by consuming less fossil fuel’. Indeed, climate change imposes a drastic and urgent transition in the metabolic patterns of societies. The objective of keeping the greenhouse gas concentration below the 450 ppm CO₂ –eq. threshold, necessary to keep temperature rise below 2°C with some acceptable probability, requires to transform the energy systems as fast as possible. Most governments dedicate a substantial part of their policies at improving energy efficiency in different economic sectors. Sustainability concepts that rest on the idea of resource- or energy-efficiency improvements due to technological progress tend to overestimate the potential saving effects because they frequently ignore the behavioural responses evoked by technological improvements. Efficiency improvements also affect the demand for resources and energy, and often an increase in efficiency by 1% will cause a reduction in resource use that is far below 1% or, sometimes, it can even cause an increase in

* E-mail : snemot@ulb.ac.be; Tel: (+33) 6 17 23 27 45

resource use. This phenomenon is commonly labelled the rebound effect, which is well-known among energy economists, but never attracted much attention.

If the rebound effects have been seriously underestimated or neglected by both experts and policymakers, over the past thirty years, overall household energy consumption has risen in spite of the energy-efficiency innovations in accommodations and mobility. The energy use of a car produced thirty years ago is higher than a current car, but the total fuel consumption in the countries of OCED is nowadays above past average, with a gap of 60 percent. In the same way, the current housings of industrialized nations are more economical than buildings built thirty years ago, however, they are also bigger. For instance, the surface area per French citizen has increased from 25 to 38 m² between 1973 and 2006 (Ademe, 2010). Consequently, the important changes required for making the energy transition successful challenge public authorities at all levels for designing and implementing effective, efficient, equitable, comprehensible and acceptable policies and measures. The acceptability or the 'desirability' of such energy policies and measures are crucial to transform a theoretical reflection into concrete improvements. As climate policies are no longer achieving the energy savings we need, their unexpected effects will be explored by a sociological approach in this talk. What do the rebound effects mean for households' practices?

If we take the social organisation of everyday life as the main focus, it is immediately apparent that rather than concentrating on 'resources' like energy, the key issue is on of first understanding the services of these resources make possible: heating, lighting, cooking etc. and then thinking about how these services change. Before exploring ways of conceptualising and investigating transitions in practice, I would like to briefly review a range of economic studies on the rebound effects. To understand how the energy efficiency of appliances is thrown back into doubt by increased use of the product, or greater use of the product, or greater use of another, we will deepen existing scientific knowledge. Then, theoretical considerations as well as empirical evidence from a research in progress in Belgium will be able to question the long-held paradigm of consumers' rationality. But, first, what do we know about the rebounds effects in the energy-related practices of households?

2. ECONOMIC LITERATURE REVIEW ON REBOUND EFFECTS, FROM A SOCIOLOGICAL POINT OF VIEW

Rebound effect is often mentioned in different disciplines. It is an important question of research for medical sciences like general and dental medicines, cardiology, neurology, toxicology, pharmacology or psychiatry. They define rebound effect as a suppression of sickness that appears later or when other symptoms happen. Technical sciences consider the meaning of rebound effects as economists explain them. Regarding energy sector, social sciences rarely explore these unexpected phenomena of energy efficiency beyond the evocation of the mechanism as an explanation. So, the starting point consists in the state of economic art about rebound effects in household energy consumption. As a sociologist, my discipline has its own shortcomings about the problem but also the potential of new thinking. Thus, I would like to address key issues to the argument of rebound effects in domestic metabolism of energy and, then, the conceptual framework of typical approaches in economics will be deepened.

2.1. Typical approaches to rebound effects in household energy consumption

To start, we need to understand how energy economics analyse the rebound effects. To this end, a short introduction to scientific foundations will go back to the beginning. Afterwards, economic literature review on rebound effects will follow a double line of analysis. Macro-level first, a view from the micro side comes after. As our point of view is concerned with household energy use only, a way forwards is to enter into details of the micro-economic approaches to rebound effects.

2.1.1. Scientific foundations of rebound effects in energy economics

The rebound effect is generally expressed as the ratio of the lost benefit compared to the environmental benefit when holding consumption constant. This discrepancy is known as the energy efficiency gap. A part of this gap is attributed to “barriers” that impede the full exhaustion of the theoretical efficiency potentials. Another part of the gap is due to “rebound effects”, and is usually measured as a percentage of engineering savings (Sorrel, 2009). A first systematic treatment can be found in Brookes (1979) and, later, in Khazzoom (1980), leading to the Khazzoom-Brookes or KB postulate (a term coined by Saunders (1992)), which states that energy efficiency improvements justified at the micro-level leads to levels of energy consumption at the macro-level which are higher than they would have been in the absence of those improvements. Thus, the two opposing positions can be summarized as, first, total energy use is higher than if there had been no efficiency response and, second, total energy use is lower than if there had been no efficiency response. When the rebound effects are higher than 100%, the effect is called ‘backfire’. Furthermore, we can note that the scale of observation is a watershed of typical approaches to rebound effects in household energy consumption. In energy economics, one commonly focuses on the effects that the lower costs of energy services², due to technological improvements, have on consumer behaviour, both individually and economy-wide. So, the state of the art will recap the distinctions of rebound effects between the different dimensions of phenomena.

2.1.2. Overview of macro-economic rebound effects

At the macro-level, the rebound effects consist of two types: direct and indirect. The ‘macro-economic’ or ‘economy-wide rebound effects’ imply that decreased demand for a resource leads to a lower resource price making new uses economically viable. The ‘direct rebound effect’ is the increased total consumption of the energy service under consideration. This type of rebound effects is the sum of the substitution effect and the (direct) income effect. The ‘direct rebound effect’ is closely linked to the elasticity of substitution. The ‘indirect rebound effect’ also depends on the elasticities of demand for each of the goods or services, and the energy consumption associated with each commodity (a price or income elasticity is the ratio of the percentage of change in demand to a percentage of change in price or income). Indeed, the ‘indirect (income) effect’ or ‘product substitution effect’ is the increased consumption of other final consumption goods and services by households. Since our sociological point of view focuses on households, our attention will mostly go to the complex field of energy supply and domestic demand at their level.

2.1.3. A view of rebound effects from the micro side

Indirect and direct rebound effects also play at the micro-level of an energy service. The distinction is underlined by large and small scales in energy economics. Moreover, other disciplines like medical ones distinguish two types in rebound effects. For micro-economists, a ‘direct effect’ whereby households consume more of the energy service, after energy-efficiency improvements, and an ‘indirect effect’ whereby consumers increase their consumption of other goods or services. The individual may, for example, decide to spend more money on ‘luxury’ services, e.g. going on holiday by plane. This is also an income effect, because the budget (or nominal income) of the household is still not used up after enjoying the (extra) quantity of the energy service which is under consideration with its energy-efficiency improvements. Energy efficiency is defined as the ratio activity/energy. Energy efficiency as a means to consume less energy is generally agreed. While it is quite easy to calculate energy intensity of an economy, energy efficiency is much more difficult to calculate. It depends on the definition of the service

² Energy service means here any service provided to households and that uses energy, whatever is the energy vector or the technological system.

provided by an activity and its possible substitution. It is supposed to be purely technological and discards any 'behavioural interference' that raises key issues about empirical evidence for rebound effects in household energy consumption.

2.2. Key issues addressed to the argument of rebound effects in domestic metabolism of energy

2.2.1. An assessment of empirical evidence for rebound effects in household energy consumption

Economists seek to identify through long-term studies and mathematical models the importance of the rebound effects and also the conditions causing the rebound effect to exceed 100%. In energy economics, the existence of rebound effects is admitted and observed but, among the experts, opinions diverge on the significance of the rebound phenomena with the latest research (Sorrel, 2007) showing it may be the most important factor for explaining why energy use is not declining (without economic crisis). The current report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre, notices that empirical investigations are rare, ambiguous and, often not very conclusive (Sorrel, 2007). There are very few quantitative estimates of economy-wide effects, but several studies suggest that these may exceed 50% in some cases. The evidence and arguments used in support of the backfire hypothesis are insufficient to demonstrate its validity, but nevertheless pose an important challenge to conventional wisdom. There is a large body of literature suggesting that the direct rebound effect is indeed real with regard to personal transport (Greene et al., 1999; Jones, 1993; Johansson & Shipper, 1997; Haughton & Sarkar, 1996; Small & van Dender, 2005; West, 2004), space heating (Schwarz & Taylor, 1995; Hsueh & Gerner, 1993; Klein, 1987; Guertin et al., 2003; Haas & Biermayer, 2000) and other consumer energy services in OECD. For these different sectors and major end-uses, the econometric studies and direct measurements of the rebound effect find that the effect is in the range of 10-40%. However, all assume 'pure' energy efficiency improvements. Thus, the basis to draw any general conclusions is inadequate. Furthermore, we can note many methodological deficiencies.

2.2.2. Variety of methodological problems

In macro-economics, one cannot run 'control' experiments, to verify whether energy consumption is lower or higher than if there had been no efficiency improvements. Key problems are numerous. Firstly, rebound effects differ by end-use and sector of the economy. Secondly, responses at the micro-level (e.g. consumers) are different than those at the macro-level (regional economy). Besides, the results depend to a large extent on the assumptions about the elasticity of substitution of energy for other factors of production. In micro-economics, the studies on rebound effects usually concentrate on the demand of one particular energy service such as mobility or room temperature. Subsequently, they tend to overestimate price effects, whereas Lovins claims that the rebound effect is more likely to be an income effect rather than a price effect (1988, p. 158). There is no evidence that would question the relevance of the rebound effect even in a multi-service model. On the contrary, the feedback will even be stronger than suggested by the single-service model if substitutability between services is high and if the demand for energy increase with income. In addition, only energy was explicitly considered as an input to the production of the service. However, other inputs may also be relevant for the production of energy services, such as capital goods and 'time' (e.g. the time necessary for driving a certain distance). Lastly, implicitly the economic model assumes reversibility of investment in energy saving devices. Households would, therefore, constantly adjust their capital stock to new optimal levels whenever capital and energy prices change. This assumption seems to be questionable. It relies on the neo-classical framework about energy consumers that need make an appraisal of its theoretical arguments.

2.3 Questionable assumptions of the neo-classical framework about energy consumers

In the neo-classical model, the main attributes given to consumers revolve around a strikingly limited understanding of the social world and how it uses energy resources. Indeed, from a sociological point of view, at least three principles of the conceptual framework seem to be out of touch with metabolic patterns of societies.

2.3.1. A restrictive understanding of consumer's rationality

The starting point for the discussion of neo-classical model of consumer behavior is the familiar 'rational choice model' that guides micro-economic analysis of rebound effects. This model contends that consumers make decisions by calculating the individual costs and benefits of different courses of action and choosing the option that maximizes their expected net benefits. In other words, the rationality given to consumer by the neo-classical model is instrumental and insatiable wants for goods (Stagl & O'Hara, 2001). Hence the rebound effects can be seen direct as well as indirect. However, in social sciences like sociology or anthropology, researchers observe that the consumer has not a fixed and stable way of thinking but, plural that is to say: instrumental, axiological, institutional and cognitive. These different rationalities are above all limited and the neo-classical economists do not share the same analysis about consumer's intelligence.

2.3.2. The unreasonable attribution of cognitive capacities

The economy explains how the members of society spend their financial resources, how they evaluate different possibilities and how they take purchasing decisions with the purpose of maximizing their satisfaction. A 'rational' behaviour is the result of processes of cognitive deliberation. Individuals are defined as rational and fully informed consumers by economic theories. But, for instance, services markets are characterized by the great variety of products in a given sector: comparing the available products requires considerable capacities for researching information and equally considerable capacities for analyzing it. The neo-classical model fails to take account of a number of constraints or relations: the role of institutions and of social relations, the different temporalities and spaces (that explain diversity of preferences and their sometimes fast evolution). That's why the neo-classical model of individuals, and societies by aggregation, is so static.

2.3.3. A static model of households' energy practices

The *Homo economicus* model does not describe the processes in methods of structuring, failing to explain changes of preferences and of consumption patterns. The neo-classical is individualistic, not explaining the dynamics of households' energy practices or why people make a commitment to collective actions. It is also utilitarian, failing to take "non-consumption" choices into consideration. For instance, the assumption of self-interested behaviour is contradicted by the fact the members of household help each other altruistically. Social and environmental norms are also respected even though people do not benefit from them. In the approach of energy economics, the ordinary consumer is something of a rational automaton and consumer preferences are exogenous to the model, that is to say they are taken as given without elaboration as to their origins or antecedents. To be succinct, a colleague of mine at the Centre for Studies on Sustainable Development: Gregoire Wallenborn, says that "the strength of this model resides in its performative effects, including the selection of policy instruments. Since the consumer is rational, if his purchases do not correspond to theoretical projections, it is because he is poorly informed. So, it is crucial to give adequate information to consumers. Many implemented policy instruments are oriented towards information for one believes that consumer's choice is based on information" (Wallenborn, 2007, p. 61).

It is grounds for energy efficiency policies. But, as it is well known, the problem of a laboratory science like mathematical models in energy economics is to extend facts and phenomena beyond the walls of the laboratory. As regards the micro-economic

approaches to rebound effects, there are some energy practices that can be studied in real-life like personal transport, space heating, cooking, washing etc. So, the research in progress³ proposes to revitalize the discussion, by rethinking the conceptual framework of rebound effects through an empirical approach, and with a sociological model linking practices and observable variables.

3. SHARPENING A SOCIOLOGICAL INSIGHT OF REBOUNDS EFFECTS IN ENERGY RELATED PRACTICES

It is notoriously difficult to quantify rebound effects, even the direct ones. It is therefore relevant to develop complementary, qualitative, methods to observe rebounds within households. Here are new areas of inquiry and to understand the drivers of such processes, our sociological approach surveys the users' vision of energy savings. The interest in social sciences is double. Firstly, the disciplines are grounded on field study and, secondly, their analysis about changing patterns of daily life in these terms is a way to explore the relations between energy, activity and income. Thus, the lessons from a case study can help to identify opportunities for making better use of existing scientific resources and, then, these theoretical considerations will be a basis to conceptualize the metabolism of energy efficiency in ordinary practice. But, before a social science of rebound effects emerges, we need to know why households use energy savings as they do.

3.1. New areas of inquiry: the users' view of energy savings

At the Centre for Studies on Sustainable Development (CEDD-IGEAT, University of Brussels), I am in charge of the research project entitled: "Household Energy Consumption and Rebound Effect". The HECORE project began in April 2010, with the aim of studying the rebound effects linked to the increased efficiency of energy use by Belgian households. Furthermore, an analysis will focus on the policy instruments to attenuate, neutralize or possibly prevent the counterproductive phenomena of rebound. As the research is still in its early stages, it offers a first exploration of users' imaginaries towards embedding energy consumption in practice. The empirical results will be summed up. Then, their divergences from the neo-classical framework will be analysed.

3.1.1. An empirical exploration of co-evolving imaginaries towards embedding energy consumption in practice

During this summer, focus groups were realized in Brussels, with individuals selected according to criteria based on household income, composition, age, gender and dwelling location (big cities, small towns, suburbs or countryside). These diversified panels are advantageous to maximize exploration of different perspectives within a group setting. The idea behind the focus group method is that group processes can help people to explore and clarify their views in ways that would be less easily accessible in a one to one interview. The method is particularly useful for exploring people's knowledge and experiences. It was used to examine not only how Belgian households save energy at home, or in mobility to work, but what they think about and why they think that way. The first results suggest co-evolving imaginaries towards embedding energy consumption. Indeed, several sociological studies on the changes of behaviours towards environment friendlier ways have demonstrated that individuals are not just taking in new information or environmentally oriented advice as such, and then behaving accordingly. As regards energy savings, and according to the respondents of focus groups, public awareness campaigns have an influence, notably on investments in energy efficiency at home

³ In this inter-disciplinary project entitled: Household Energy Consumption and Rebound effect, the Centre for Studies on Sustainable Development (IGEAT – University of Brussels) works with the University of Anvers, the Institute ICEDD and the Belgian Science Policy Office whose funding makes the research possible.

(insulation, heater, photovoltaic modules, electrical domestic A++, or adjustable pliers and economic lightings), and also on rational energy uses for mobility to work, by limiting the petrol consumptions of car (carpool, LPG fuel, public transports, biking or walking). In the focus groups about energy savings, households criticize passive behaviours in everyday life but, they also understand people who have fun with traveling by plane. In spite of a same discourse about the responsibility for environment, they consider energy consumption as a right and they use their energy savings to more enjoyments and pleasures like: cinema, restaurants, and sports in club, clothes, food or motorbike during week-ends. These energy related practices are several examples of indirect rebound effects in consumerist society. As for direct rebound effects, households do not perceive in their ordinary activities. They talk more about their efforts for energy savings. Their cognitive capacities do not seem to be such as the neo-classical model defines. Indeed, in this case study, we can identify divergences from the theoretical assumption of perfect information and other traditional economic postulates.

3.1.2. Lessons from a case study: divergences from neo-classical vision

The neo-classical framework of rebound effects do not really echo Belgian household's experiences described by the respondents of focus groups about energy savings. It is only a case study but it provides divergent clues. According to respondents, there are many strains on rational uses of energy. They have no sufficient time to be full informed and changes in energy related habits are considered as very long processes. In the same way, investments in energy efficiency are not a simple matter of willpower a period of economic crisis. Besides, stories about friends' criticism for being stingy were collected and they suggest that individuals are not only self-interested. Thus, it seems that the neo-classical model misses many understanding elements of rebound effects in energy practices. That's why we are interested in another model which tries to integrate them.

3.2. Conceptualizing the metabolism of energy efficiency in ordinary practice: an emerging model

An essential question of the HECORE project is to define properly the metabolism of energy efficiency in ordinary practice. It is hence needed to overcome single-service models and look into relations between goods that have different elasticities of substitution. A key aim of this research is to provide a heuristic model for exploring the energy related activities of households and conceptualizing the shift induced by an introduction of more efficient equipments. To this end, our new approach to human energy-related behaviour is inspired of practice and transition theories in social science. They will be explained firstly and then, we will use these scientific resources to sharpen a sociological insight of rebound effects in households' energy consumption.

3.2.1. Thinking about practice and transition theories

Some models are good at describing internal (cognitive) aspects of individual decisions but fail to reflect the importance of contextual or situational variables and vice versa. Making sense of behaviour inevitably requires a multi-dimensional view which incorporates both internal and external elements. A 'practice theory' approach is perfectly in line with such a perspective. In this framework, "A 'practice'... is a routinized type of behaviour which consists of several elements, interconnected to one another: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (Reckwitz, 2002). Practice theory considers that social change is linked to heterogeneous elements: artefacts, representations, skills. Transition theory analyses the multi-level interactions of these elements whose timings of change are variable if they take part in niche-innovations, socio-technical regimes, or the landscape level (Geels, 2004). Thus,

practice and transition theories inspire new ways of seeing energy consumption patterns, closer to what occurring in housing.

3.2.2. Understanding the elements of energy related practice as a complex constellation

As I hope to show, efforts to conceptualize and explain the transformation of energy related practice demand and require engagement with a significantly different set of concerns and considerations. Indeed, this perspective implies that we take account of fluid and sticky relations between practices, and between practices, and between the materials (not only the objects of energy-efficiency innovations but including infrastructures at the landscape level); images and forms of competences and understanding of which practices are themselves composed. To clarify this sociological approach to rebound effects in households' energy consumption, the emerging model will be applied to the practice of space heating in which the existence of rebound effects is well admitted by the economists. How does the practice transform when central heater is acquired and enters a household?

If we compare this energy related situation with its common practice in 1900, we observe that central heaters are actively appropriated or domesticated to the detriment of coal or wood stove. In the material field, this introduction of energy efficient technology is accompanied by the putting in radiators and pipes, even by an extension of surface area per household. However, all the residential stock of buildings is not changed. It is an element at the landscape level whose timing of innovation is very slow-acting. On the other hand, I can notice a shift in the socio-technical regime of heating. During the past winters, indoor temperatures were between 25 degrees C in the kitchen and 15 degrees C in other room. Nowadays, all the rooms of housings are routinely heated to 21 or 22 degrees C, this is what households come to expect and when that happens, anything else is deemed odd. Contemporary regimes of comfort are constituted through a range of regulations and technical procedures, knowledge of thermostats' functioning, understandings of ordinary indoor clothing, global building materials and air-conditioning industries, conventions of ventilation, sweat and smell, and actual built environments designed and run in a particular way.

The modern way of heating gathers all these elements which change the complex constellation of practice. Indeed, in the past, heating with a coal or wood stove brings together the heat for cooking, washing bodies and clothes, spending time in family. As this system of practices occurred in the same room, we can understand the mechanisms of rebound effects in the use of more efficient central heating. This appliance makes possible a new compartmentalization of ordinary practices which separates in the everyday life and in domestic spaces different sectors of household activity, i.e, heating, cooking, showering, etc. Finally, we gain an insight about this social metabolism of energy efficiency and how it increased households' energy consumption

4. CONCLUSION AND POLICY IMPLICATION

Focusing on the evolution of practices, this original analysis has shown that their implementation in a socio-technical regime leads households to organize their activities in a different way. The meanings of these transformations are diverse and the key issues of comfort, commodity and temporal gains have notably been underlined to the extent that they allow the spread of new energy services. Thus, the practices accomplished by a household have been multiplied and diversified for some time past. As a matter of fact, in the socio-technical transition of heating from coal stove to central heater, practices have been scattered at home as and when new objects were acquired by households. To conclude this attempt at rethinking the idea of rebound effects in energy micro-economics, from households' point of view, two points are important to be underlined. The first consists in the need for developing the sociological approach to the energy efficient changes in the contemporary systems of ordinary practices, with a better understanding of economists' concerns. The second point is about the policy implications of this conceptual

and empirical framework. The analytical continuation through income deciles seems significant in the examination of social cohesion (including energy poverty). As policies cannot treat the whole population as a group, the analysis by income groups could help to develop adequate policies, supported by targeted instruments.

REFERENCES

- Ademe, (2010), "Les effets rebonds des mesures d'efficacité énergétique : comment les atténuer ?", *Ademe&Vous*, n°24, Paris, Stratégie&études.
- Brookes, L., (1979), "A Low Energy Strategy for the UK by G Leach et al: a Review and Reply", *Atom*, 269, 3-8.
- Geels, F.W., (2004), "From sectoral systems of innovation to socio-technical systems, Insight about dynamics and change from sociology to institutional theory", *Research theory*, 33, 897-920.
- Greene, D. L., Khane, J., Gibson R., (1999), "Fuel economy rebound effect for US household vehicles", *Energy Journal*, 20, 1-32.
- Guertin, C., Kumbhakar S., Duraiappah A., (2003), *Determining demand for energy services: investigating income-driven behaviours*, International Institute for Sustainable Development.
- Haas, R., Biermayer, P., (2000), "The rebound effect for space heating – Empirical evidence from Austria", *Energy Policy*, 28 (6-7), 403-410.
- Haughton, J., Sarkar, S., (1996), "Gasoline tax as a corrective tax: estimates for the United States, 1970-1991", *The Energy Journal*, 17(2), 103-126.
- Hsueh, L., Gerner, J.L., (1993), "Effect of thermal improvements in housing on residential energy demand", *Journal of Consumer Affairs*, 27(1), 87-105.
- Johansson, O., Shipper, L., (1997), "Measuring the long-run fuel demand of cars: separate estimations of vehicle stock, mean fuel intensity and mean annual driving distance", *Journal of Energy Policy*, 37, 1456-1469.
- Jones, C.T., (1993), "Another look at U.S. passenger vehicle use and the 'Rebound' effect from improved fuel efficiency", *The Energy Journal*, 14(4), 99-110.
- Khazzoom, D.J., (1980), "Economic implications of mandated efficiency standards for household appliances", *Energy Journal*, 1, 21-40.
- Klein, Y.L., (1987), "An econometric model of the joint production and consumption of residential space heat", *Southern Economic Journal*, 55(2), 351-359.
- Lovins, A.B., (1988), "Energy saving from more efficient appliances: another view", *Energy Journal*, 9, 155-162.
- Reckwitz, A. (2002), "Towards a Theory of Social Practices. A Development in Culturalist Theorizing", *European Journal of Social Theory*, 5, 243-263.
- Saunders, H., (1992), "The Khazzom-Brookes Postulate and Neoclassical Growth", *Energy Journal*, 13, 131-148.
- Schwartz, P.M., Taylor, T.N., (1995), "Cold hands, warm hearth?: climate, net takeback, and household comfort", *Energy Journal*, 16(1), 41-54.
- Small, K.A., Van Dender, K., (2005), *The Effect of Improved Fuel Economy on Vehicle Miles Traveled: Estimating the Rebound Effect Using U.S. State Data, 1966-2001*, University of California Energy Institute's (UCEI) Energy Policy and Economics Working Paper Series.
- Sorrel, S., (2007), *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*, A report produced by the Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre, UK-ERC.
- Sorrel, S., (2009), "Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency", *Energy Policy*, 37, 1456-1469.
- Stagl, S., O'Hara, S. U., (2001), "Preferences, needs and sustainability", *International Journal Sustainable Development*, Vol. 4. 1, 1-18.
- Wallenborn, G., (2007), "How to attribute power to consumers? When epistemology and politics converge", in *Sustainable Consumption, Ecology and Fair Trade*, E. Zaccai (ed.) London, Routledge, 57-69.
- West, S.E., (2004), "Distributional Effects of Alternative Vehicle Pollution Control Policies", *Journal of Public Economics*, 88 (3-4), 735-757.

ROMANIAN METABOLISM AND SUSTAINABLE POLICIES (MUSIASSEM AT LEVEL N-4)

Raluca I. Iorgulescu^{*1,2}, Lucian-Liviu Albu², Cristian Stanica², John M. Polimeni³

¹ Economics Department, Siena College, 515 Loudon Road, Loudonville, NY 12211, United States of America

² Institute for Economic Forecasting, Casa Academiei Romane, Calea 13 Septembrie, No. 13, Sector 5, Bucharest RO-050711, Romania

³ Albany College of Pharmacy, 106 New Scotland Avenue, Albany, New York 12208-3492 United States of America

ABSTRACT

Multi-Scale Integrated Analysis of Societal and Ecological Metabolism (MuSIASEM) is a method developed in relation to the field of science for governance and it can be used to check the robustness and the relevance of models, datasets, and forecasting using integrated biophysical, economic, social and demographic analyses across different hierarchical levels and scales. This paper considers the period 1999-2006 and presents an analysis, with industry-level details and through MuSIASEM lenses, of the economic changes experienced by the Romanian economic system in the move towards the European Union member status. The Romanian exosomatic metabolism is analyzed on five hierarchical levels: national level (*level n*); *level n-1* is divided between the production compartment (paid work) and the consumption compartment (households); *level n-2* is the split of the previous level in the corresponding sectors (agriculture, industry and services and government). The bottom lower levels, *level n-3* and *level n-4* decompose the productive and commercial and public services sectors in specific industries. The results are provided together with details regarding the microeconomic changes in industries with high exosomatic metabolism. The evolution of the energy metabolism intensity (exosomatic metabolic rate) for different groups of industries (*level n-3*) and industries (*level n-4*) is presented and explained. For *level n-3* we consider the following subsectors for the productive sector: mining and energy and manufacture and building. Similarly for the services and government sector we consider as subsectors: transport, public administration and other sectors. Each of these subsectors (except for public administration and other sectors) can be split further at *level n-4*. Structural changes in each economic sector can be related to metabolic variations and the paper provides microeconomic details for specific industries to support this statement. The study creates the foundation for a future analysis comparing the development of Romania with that of Catalonia and, possibly, Ireland.

Keywords: MuSIASEM, Romania, societal metabolism, energy, sustainable policies

1. INTRODUCTION

Romania is a country which switched in December 1989 from a command system to a free-market system and joined the European Union on January 1st 2007. Post-Revolutionary Romania had to undergo a “quintuple transition: building from scratch political, civil and economic societies; developing an autonomous yet accountable state bureaucracy and all the while constraining these aforementioned areas through the development of the rule of law and an independent judicial system to enforce the equal rights of Romania’s citizenry” [Turnock 2009, p.9]. Even in 2000, the Romanian institutional system was still not restructured and it was highly bureaucratic and inefficient

* Corresponding author; E-mail: riorgulescu@siena.edu; Tel: 001 518 783-4144

in impossibility to support the free-market transition. To make things worse, besides populist political interests, labor unions have not been a responsible partner for the government when a severe reform program was needed (including e.g. the closing the underground mines, the liberalization of energy price, and breaking the state monopolies). Privatization was delayed until 1996 or it targeted only populist aspects and the consequence was that “the administrations before 1996 saddled the business people with two difficult burdens they had to cope on the long term... the deep hostility of the population, generated by the objective fact that a lot of fortunes had been accumulated in a quasi-illegal manner. The latter is the false impression of the private entrepreneurs themselves that their business could always be conducted under the umbrella of the State...” [Serbanescu 2007, p.52-53].

The communist industrial model, promoting the energy-intensive industrial sector with a use of energy per unit of output much higher than in Western countries, was already declining in 1989, leaving post-Revolution Romania with an inherited enormous economic gap between demand and offer [Serbanescu 2007, p. 31]. For eleven years, Romania did not have a clear strategy for development; only in 2000 it was demanded for European Union integration and in this context, Romania was required to reduce national energy consumption and increase energy efficiency at the end-use.

Nicholas Georgescu-Roegen [1971] emphasized the irreversibility of the economic process and the effect of the entropy law governing physical and biological processes and introduced the flow-fund model promoting the concepts of societal metabolism and bioeconomics. Multi-Scale Integrated Analysis of Societal and Ecological Metabolism (MuSIASEM) is a method developed [Giampietro and Mayumi 2000a, Giampietro and Mayumi 2000b, Giampietro 2003, Giampietro, Mayumi and Ramos-Martin 2009] in relation to the new field of science for governance and it can be used to check the robustness and the relevance of models, datasets, and forecasting using integrated biophysical, economic, social and demographic analyses across different hierarchical levels and scales. This paper applies the MuSIASEM approach to the study of structural changes in Romanian economy between 1999 and 2006 in country's move towards the European Union member status and it has the purpose to build the Romanian database and the set of MuSIASEM intensive and extensive indicators down to level $n-4$.

Iorgulescu and Polimeni [2009] present the MuSIASEM approach to analyze Romanian socioeconomic system as a whole (level n) and disaggregated on two successive hierarchical levels ($n-1$ and $n-2$); the comparison is made with other European countries. The split between paid work compartment and households compartment represents level $n-1$, while the split of the paid work compartment in three main sectors (agriculture AG, productive sector PS, and commercial and public services SG) represents level $n-2$. The present study depicts the Romanian exosomatic metabolism for two additional lower levels ($n-3$ and $n-4$) of the productive and commercial and public services sectors. Those sectors are split into groups of industries (mining and energy, manufacture and building, and transport for level $n-3$) and subsequently into individual industries for each group (level $n-4$). Some details are provided regarding the microeconomic changes of industries with the top exosomatic metabolism.

The study is organized as follows: section 2 presents data processing details for the three types of data: energy, hours of work in each paid-work activity, and gross domestic product (very important details when the economy is disaggregated down to level $n-4$); section 3 presents, using graphs, level $n-3$ and $n-4$ results for MuSIASEM exosomatic metabolic rate; finally, section 4 concludes.

2. DATA COLLECTION

ENERGY

Data source

Statistical data are presented within the *final energy system*. The data source consists of the annual statistical surveys of the production of electricity and thermal energy, energy resources and their use, resources and consumption of electricity, thermal energy, fuels, motor fuels and lubricants.

Besides them, specialized annual statistical surveys, with pre-established destination, are used:

- Production of electricity and thermal energy in nuclear power stations
- Crude oil processing balance sheet.

The nomenclature on which reporting is based consists of 13400 units (firms)

Data collection is exhaustive in case of units belonging to the industry producing electricity and thermal energy, industrial consumers with over 250 employees and consumers from transports, construction and services with over 50 employees, while for the remaining units a representative sample for CANE Rev.1 activities is taken over.

Data on international trade in goods

This data is obtained as follows: for the extra-community trade from the National Customs Authority (NCA), which carries out export and import custom statements collection and processing; for those referring to intra-community trade, through Intrastat statistical statements collected by the National Institute of Statistics (NIS) from economic agents which have achieved intra-community exchanges (in accordance with Law no. 422/2007) and based on customs statements related to intra-community trade exchanges supplied by NCA.

Population energy consumption

For households, the information was completed with data obtained from Household Budgets Survey, thus being included the quantities of fuels obtained from own activities of population households.

- In this study, fuel consumption in households' private transport means is included under Households consumption (ET_{HH}).
- The statistical data series for all energy indicators refer to the period 1993 - 2007.
- The conventional unit is tonne of coal equivalent, defined by convention as a fuel of 29307 KJ/Kg (7000 Kcal/Kg) net calorific value.
- The indicator Energy consumption in transports – road transport was separated in Population energy consumption and Energy consumption of other economic agents
- For the period 1999 – 2007 the data series are available at the most disaggregated level, while for the period 1993 – 1998 the following aggregated activity branches are available, whose components have been estimated based on the structure of this aggregated activity branch:
 - ❖ Consumption in energy sector
 - Coal mining and preparation (including bituminous schist's and sands) - NACE, code 10
 - Oil and natural gas extraction (excluding prospecting) - NACE, code 11
 - Crude oil processing, coal coking and nuclear fuels treatment - NACE, code 23
 - Production and distribution of electricity and heat, gas and hot water - NACE, code 40
 - ❖ Consumption in sector of metal products, machinery and equipment
 - Manufacture of fabricated metal products, except machinery and equipment - NACE, code 28
 - Manufacture of machinery and equipment n.e.c. - NACE, code 29
 - Manufacture of office machinery and computers. - NACE, code 30
 - Manufacture of electrical machinery and apparatus n.e.c. - NACE, code 31
 - Manufacture of radio, television and communication equipment and apparatus - NACE, code 32

- Manufacture of medical and optical instruments, watches and clocks - NACE, code 33
- Manufacture of motor vehicles, trailers and semi-trailers - NACE, code 34
- Manufacture of other transport equipment NACE, code 35
- ❖ Consumption in transport sector
 - Air transport
 - Freight transport by road
 - Transport via railways
 - Water transport
 - Transport via pipelines

HUMAN ACTIVITY

The data used in the present study for *hours actually worked* in the production sector and services and government are based on the *Survey on the labour cost (S3)* which collects the information provided by firms about their employees; for agriculture we used the data provided by the *survey of households AMIGO* (since in Romanian agriculture there are very few firms and using the information from firms survey would distort the results).

GROSS DOMESTIC PRODUCT AND TAXES

The computation of GDP for industry 'i' (levels lower than $n-2$):

$$\text{GDP}_i = \text{Value-added}_i + \text{Net Taxes}_i \quad (1)$$

$$\text{Net Taxes}_i = \text{Tax revenue}_i - \text{Subsidies}_i \quad (2)$$

Data source

- The statistical series of gross value added components by activity branches are taken over from the Input – Output Table compiled according to the National Accounts methodology. These data are supplied by the National Institute of Statistics for each year, both in current prices and in comparable prices of previous year.
- The database of net taxes on products was built up based on the same structure by activity branches, both in current prices and in comparable prices of previous year. The information from the Input – Output Table has been used.
- The data from the Input – Output Table are available until 2006, inclusively, in accordance with Eurostat requirements; for 2007 no further detailed computations could be done due to the lack of statistical information.

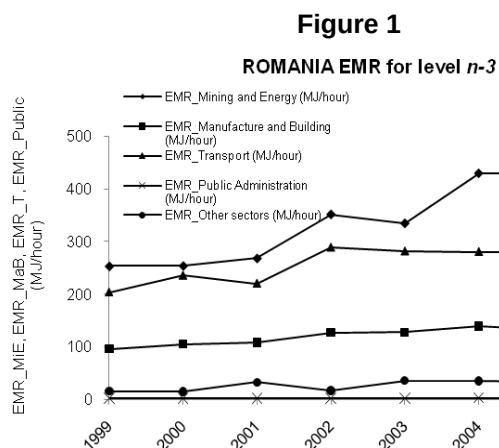
Statistical processing

- Statistical processing refers to the computation in constant prices of the year 2000 of statistical series by activity branches related to gross value added and to net taxes on products.
- During the first stage, chain volume indices were compiled for each year as compared to previous year by using the data series in comparable prices of previous year and the data series in current prices
- During the second stage, the volume indices were compiled for each year as compared to the year 2000 considered as 100%. The data series in constant prices of the year 2000 were recompiled by multiplying these indices with the values expressed in current prices of the year 2000.
- The following three industrial branches were compiled by summing up the components:
 - Mining and quarrying industry
 - Manufacturing
 - Electricity and thermal energy, gas and water
- The three aggregated series were compiled in constant prices of the year 2000: total industry, gross value added and net taxes, while the gross domestic product was compiled by summing up the latter two series.

- The series Other services was compiled by subtracting the other components from the gross value added, otherwise this series being biased due to statistical discrepancies, but the error is below 1%.

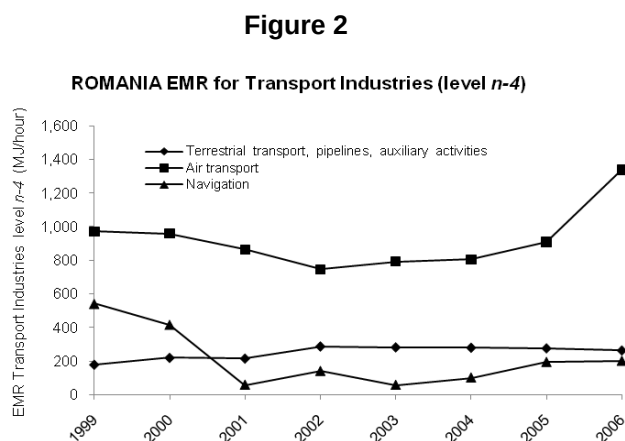
3. MUSIASSEM EXOSOMATIC METABOLIC RATE RESULTS FOR LEVELS *N*-3 AND *N*-4

This section will present and explain the evolution of the energy metabolism intensity (exosomatic metabolic rate) for different groups of industries (level *n*-3) and industries (level *n*-4).



For level *n*-3 (Figure 1) we consider the following subsectors for the productive sector: mining and energy (MiE) and manufacture and building (MaB). Similarly for the services and government sector we consider as subsectors: transport, public administration and other sectors. Each of these subsectors (except for public administration and other sectors) can be split further at level *n*-4 (Figures 2 to 7). Structural changes in each economic sector can be related to metabolic variations and this section will provide microeconomic details for certain industries to support this statement.

It can be seen in Figure 1 that **Transport** as a whole sector has a high energy metabolism which increases until 2002 and decreases slightly afterwards. It is interesting to analyze the behavior on the exosomatic metabolic rate at a lower level (*n*-4). Figure 2 presents EMR for the three Transport industries: terrestrial transport, pipelines and auxiliary activities, air transport, and navigation.



Terrestrial transport pipelines and auxiliary activities industry shows an energy metabolism slightly increasing after 1999 and becoming relatively stable after 2002. This behavior corresponds to an industry which reached its maturity with established firms.

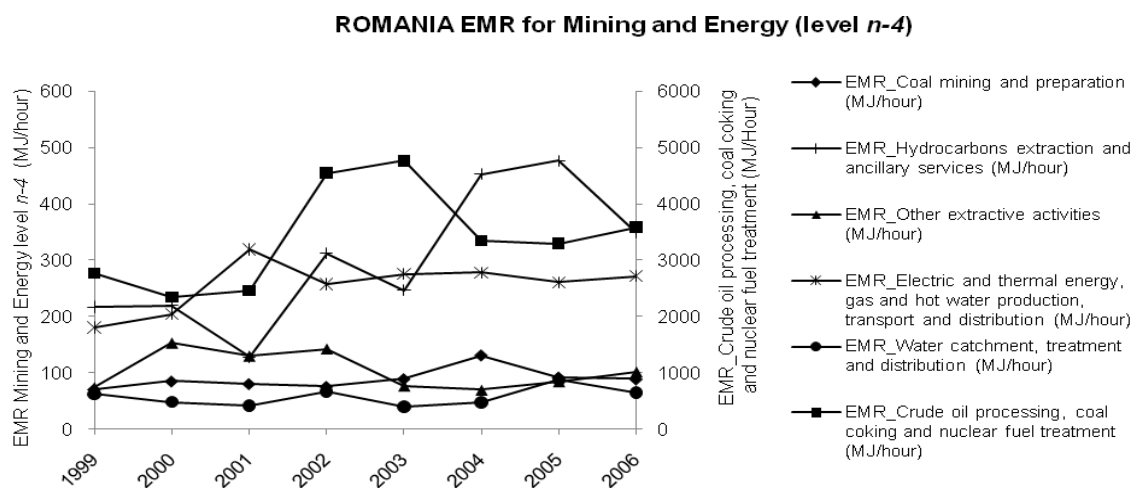
Romanian air transport industry is represented by one company, TAROM. In 2001 the airline cancelled its non-profitable long haul services to Bangkok and Montreal and also terminated services to its remaining intercontinental destinations of Beijing (in 2003), Chicago (in 2002), and New York City (in 2003). TAROM terminated some of its loss-making domestic services and focused its activity on service to key destinations in Europe and the Middle East. Year 2004 was the first profitable year of the last decade. These microeconomic changes are reflected by the decrease followed by an increase in the exosomatic metabolic rate.

Between 1999 and 2001, the Danube was blocked due to the war in Kosovo. Romania did not have a sea fleet anymore, only an inland fleet so the effects of the blockade on Danube were visible as a reduction in the exosomatic metabolic rate for navigation which sharply decreased between 1999 and 2001. The recovery was slow and the energy metabolism in the Navigation industry kept increasing after 2003.

Another sector with a high energy metabolism is **Energy and Mining**. This sector can be disaggregated further in six industries (Figure 3). Three of them (Crude oil processing, coal coking, and nuclear fuel treatment; Electric and thermal energy, gas and hot water production, transport and distribution; Hydrocarbons extraction and ancillary services) have a high energy metabolism while the other three (Other extractive activities; Coal mining and preparation; Water catchment, treatment and distribution) have a medium energy metabolism.

The spike of the exosomatic metabolic rate in the crude oil processing, coal coking, and nuclear fuel treatment industry between 2001 and 2004 is mainly explained by the reduction in the number of hours worked in this industry.

Figure 3



Crude oil processing industry is composed of ten refineries (ARPECHIM, Petrobrazii, Petromidia, RAFO Onesti, Petrotel, Astra Romana, Vega, Steaua Romana, Petrolsub si Darmanesti). After 1998, all of them were privatized and reorganized including investments and workforce adjustments. Privatized in 2000, between 2001 and 2004, Petromidia fired many of his workers and invested in technology. Petrotel was privatized in 1998 and reconstructed and modernized between 2002 and 2004. Vega, privatized in 1999, did not get modernized but it massively fired its workers.

Romania had four coal coking plants: Resita, Hunedoara, Galati, and Calarasi. Resita and Hunedoara plants were closed between 1999 and 2001, while the Calarasi plant was closed in 2000. The last plant, Galati, worked at 25% of its capacity until 2002

when it was privatized. Closing the three coal coking plants had as direct effects the reduction of work hours invested in this industry and the closing of the coal mines in Banat Mountains and of some of the coal mines in Jiul Valley (visible as a spike on the corresponding EMR graph for coal mining and preparation industry).

After 2000, following the signing of a new standby agreement with IMF, the hydrocarbons extractions and ancillary services industry was restructured. The privatization process of the firms providing ancillary services and of Petrom (oil and gas extraction) explains the ups and downs on the EMR graph.

Table 1 presents the ranking, for each year of the period considered, of eight industries with the highest energy metabolism.

4. FINAL COMMENTS

It is necessary to discuss and clarify the issue of data sources for energy consumption, hours actually worked, and gross domestic product generated at various hierarchical levels. Two types of surveys are used as data sources: households survey (AMIGO) and firms survey (S3). Households survey generates information on worked hours as provided by households and includes employees (formal and informal) and self-employed. Firms survey generates only the information reported by firms regarding their own employees. For energy consumption, all information is generated by firms survey. So, in order to obtain the MuSIASEM intensive variable $EMR_i = \text{energy throughput}_i / \text{human activity}_i$, we need to be consistent and use the information from the same survey.

Table 1. Top 8 Industries for Exosomatic Metabolism between 1999 and 2006
(1 highest, 8 lowest)

EXOSOMATIC METABOLISM TOP 8 Industries EMR level $n-4$ (MJ/hour)	1999	2000	2001	2002	2003	2004	2005	2006
1	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment	23. Crude oil processing, coal coking and nuclear fuel treatment
2	Air transport	Air transport	Air transport	24. Chemical substances and products	24. Chemical substances and products	24. Chemical substances and products	27. Metallurgy	27. Metallurgy
3	27. Metallurgy	24. Chemical substances and products	24. Chemical substances and products	Air transport	27. Metallurgy	27. Metallurgy	24. Chemical substances and products	Air transport
4	Navigation	27. Metallurgy	27. Metallurgy	27. Metallurgy	Air transport	Air transport	Air transport	24. Chemical substances and products
5	24. Chemical substances and products	Navigation	21. Pulp, paper, and paper products	21. Pulp, paper, and paper products	21. Pulp, paper, and paper products	16. Tobacco products	26. Manufacturing of construction materials and other products of non metallic minerals	26. Manufacturing of construction materials and other products of non metallic minerals
6	21. Pulp, paper, and paper products	21. Pulp, paper, and paper products	26. Manufacturing of construction materials and other products of non metallic minerals	26. Manufacturing of construction materials and other products of non metallic minerals	26. Manufacturing of construction materials and other products of non metallic minerals	11. Hydrocarbons extraction and ancillary services	11. Hydrocarbons extraction and ancillary services	11. Hydrocarbons extraction and ancillary services
7	26. Manufacturing of construction materials and other products of non metallic minerals	26. Manufacturing of construction materials and other products of non metallic minerals	40. Electric and thermal energy, gas and hot water production, transport and distribution	11. Hydrocarbons extraction and ancillary services	Terrestrial transport, pipelines, auxiliary activities	26. Manufacturing of construction materials and other products of non metallic minerals	21. Pulp, paper, and paper products	21. Pulp, paper, and paper products
8	11. Hydrocarbons extraction and ancillary services	Terrestrial transport, pipelines, auxiliary activities	Terrestrial transport, pipelines, auxiliary activities	Terrestrial transport, pipelines, auxiliary activities	40. Electric and thermal energy, gas and hot water production, transport and distribution	21. Pulp, paper, and paper products	Terrestrial transport, pipelines, auxiliary activities	40. Electric and thermal energy, gas and hot water production, transport and distribution

This would not be an issue for aggregated (level $n-2$) productive sector PS and services and government SG; the problem arises when we analyze lower levels and agriculture since Romania is one of the countries with a very high occupancy rate in agriculture (with a subsistence type of activity) and a very low presence of firms.

If we introduce GDP in the MuSIASEM discussion for levels lower than $n-2$, the situation becomes even more complicated since we cannot correlate the GDP data with data for energy or hours of activity. We will provide a methodological explanation. When GDP is computed, it includes, for each industry, information from both firms and households. This discrepancy could be addressed for studies at lower levels in various ways.

The first solution would have three steps:

1. GDP for each industry could be divided by the number of hours computed in the same methodology as GDP. The result is the indicator GDP/hours and it shows how much of the value-added corresponds to one hour of work in that industry.
2. Energy consumption could be divided by the number of hours worked in each industry provided by firms survey.

Finally, the two indicators, GDP per hour and energy consumption per hour for each industry could be correlated in a model.

A second solution would be to use for hours worked in each sector the set of data from the National Accounts System and consider only the hours corresponding to employees (we mention that we did not use this approach since for Romania at the moment when this study was conducted were available only the data for 2002-2006 and this would have reduced our ability to conduct a cross-time analysis). The next step would be to compute, for each industry, a sort of coefficients by dividing the number of hours from the firms survey to the number of hours for employees from the National Accounts System. Such a coefficient would represent the discrepancy, for employees, between the two statistical methods and it is due to taking the ratio between work hours reported by firms (S3) and by households (AMIGO). Firms reporting data according to their main activity and for GDP computation the activity is homogenous; this is another source for the difference between the two work hours databases. For example, for building, the numbers of work hours are declared by firms (S3) with the main activity in building and considering the whole firm. These include other secondary activities of the firm besides the main activity in building. For GDP, it is computed the homogeneous building industry which sums the building section from each firm even if the firm has the main activity in a different industry.

Methodologically speaking, for industries (levels $n-3$, $n-4$ and lower), GDP cannot be compared with energy consumption since one is for a homogeneous industry and the other for a main activity industry; one includes workers officially declared by firms, unofficial (informal) workers declared by households, and self-employed, while the other considers only the official employees declared by firms.

ACKNOWLEDGEMENTS

Funding for this research was provided by the EU Project "Synergies in Multi-scale Inter-Linkages of Eco-social systems" (SMILE), Seven Framework Programme, Theme 8, Socioeconomic Sciences and Humanities (SSH), Grant no. 217213.

The authors would like to thank Sorin Dinu for his extremely valuable input to the structural change discussion.

REFERENCES

Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*, Harvard University Press, Cambridge, MA

- Giampietro, M., Mayumi, K., 2000a. "Multiple-scale integrated assessment of societal metabolism: introducing the approach". *Population and Environment* 22 (2), 109–153.
- Giampietro, M., Mayumi, K., 2000b. "Multiple-scale integrated assessment of societal metabolism: integrating biophysical and economic representations across scales". *Population and Environment* 22 (2), 155–210.
- Giampietro M., 2003. *Multi-Scale Integrated Analysis of Agro-ecosystems*. CRC Press, Boca Raton
- Giampietro, M., Mayumi, K., Ramos-Martin, J., 2009. "Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): theoretical concepts and basic rationale". *Energy* 34 (3), 313–322.
- Iorgulescu, R.I., Polimeni, J.M., 2009. "A multi-scale integrated analysis of the energy use in Romania, Bulgaria, Poland and Hungary". *Energy* 34 (3), 341–347.
- Iorgulescu, R. I., Albu, L. L. and Stanica, C. "Romania: Socioeconomic Metabolism and Sustainable Policies". Paper to be published in the *Proceedings of the 5th Annual International Symposium on Economic Theory, Policy and Applications*, July 2010, Athens, Greece.
- Serbanescu, I., 2007. *Romania Under the Tyranny of Small Figures*. East European Monographs, Boulder, CO, USA.
- Turnock, D., 2009. *The Transition from Communism to the European Union*. Edward Elgar Publishing Limited, Cheltenham, UK.

MODELLING THE ENERGY DYNAMICS OF HUMAN CIVILIZATIONS WITHIN THE THEORY OF CULTURAL EVOLUTIONISM

Georgios Karakatsanis*

National Technical University of Athens (NTUA)

ABSTRACT

The paper attempts to express mathematically the dynamics described in the anthropological theory of cultural evolutionism -mainly developed by Leslie White- which considers a civilization's ability to harness and control energy as the "primary function of culture". Within this framework, human societies are modelled as ecosystems with finite energy resources. Thus, their energy dynamics are described by a logistic growth function.

Historically, civilizations are distinguished by their dominant pattern of energy harvesting, called the *energy paradigm*. Based on that definition, the energy paradigm dynamics consist of three parameters, contained in the model; (a) *its free-energy (exergy) deposit size*, (b) *its demand* and (c) *its share in the total energy use*. All are assumed to non-linearly relate to each other constituting the energy paradigm's maximum potential amplitude and the civilization's real fuel wealth, called the *energy scale*.

As the model deploys, its mathematical attributes will be translated into natural terms. The model's overall dynamics are separated by three general stages: "Formation", "Acceleration" and "Saturation". The ratio between the parameters' values will determine the civilization's energy fate; smooth or extremely oscillating dynamics; consequently its survival and further evolution or its energy default.

Keywords: Cultural evolutionism, societies as ecosystems, "primary function of culture", logistic growth dynamics, energy paradigm, energy scale, free-energy deposit, energy demand, energy paradigm share, crowding out of energy paradigm substitutions

Nomenclature	
English Letters	Greek Letters
$i = \text{Unit } 1, 2, \dots, i$	$\varepsilon = \text{Epsilon} = \text{The energy use propensity}$
$j = \text{Unit } 1, 2, \dots, j$	$\alpha = \text{Alfa} = \text{The energy paradigm substitution coefficient}$
$t = \text{Unit of time } 1, 2, \dots, t, \dots T$	$T = \text{Tau} = \text{Life-Time of the energy paradigm}$
$E = \text{Total Energy Use}$	$\rho = \text{Rho} = \text{Rate of growth of energy use propensity}$
$ES = \text{Energy Scale}$	$\Delta = \text{Delta} = \text{Differential in } ES, T, \text{ etc.}$
$A = \text{Free Energy or Exergy deposit}$	$\beta = \text{Beta} = \text{Elasticity of } \varepsilon \text{ to } \alpha$
$ESM = \text{Energy Scale Multiplier}$	
$E_{\max} = \text{Peak of the ES under the assumption of } \varepsilon, \alpha \text{ and } A \text{ constancy}$	

CULTURAL EVOLUTIONISM AND THE "PRIMARY FUNCTION OF CULTURE"

Cultural evolutionism was primarily developed by anthropologist Leslie White, while attempting to create an energy theory for the rise and fall of human civilizations. According to his theory the "primary function of culture" was available energy –further specialized into energy technology. As White wrote [White, 1959] "*Social systems are determined by technical systems*"; echoing an earlier theory of anthropologist Lewis Henry Morgan. Leslie White considered the rapid collapse of the Western Roman Empire as the best

* E-mail: karakas11361@gmail.com; Tel.: +306945552243

case study for proving his theory. The anthropologist Joseph Tainter expanded White's conclusions by developing a more specialized energy economic theory based on *marginal productivities*, in order to explain the rapid collapse of sixteen other civilizations as well [Tainter, 1988].

However, from both studies emerged a new and important conclusion. In all cases the amount of available energy did not constitute by itself a condition for ensuring the system's sustainability, unless it was accompanied by an efficient mechanism of technology transition. This conclusion directed contemporary social research to the study of the endogenous factors of a system's energy evolution as well as the detection and remedy of its structural fallacies that would eventually threaten to lead it to a collapse.

1. MODELLING A CIVILIZATION'S ENERGY MACRODYNAMICS

What actually White and Tainter postulate is that collapsing civilizations are complex systems that continued to grow beyond the limits of their energy budget. In this way they introduced two significant concepts: the concept of (a) capacity and of (b) "metabolism", just as it stands for natural ecosystems. Human civilizations have almost every attribute needed to be modelled as ecosystems as well [Odum, 1971]. All are self-organizing growing and self-regulating systems, where the available free-energy defines their primary limits of growth.

Growing systems with finite limits are best expressed by Verhulst-type logistic functions. However, after a "critical complexity" point, a civilization's survival and evolution by no means can be taken for granted; contrarily it depends on its ability to "metabolize" available energy into sophisticated norms of managing it. These norms constitute the set of "social algorithms" for directing available energy flows [Holling, 2009]. They are the complete set of a civilization's natural attributes and the social institutions to regulate them; like population, R&D, the monetary system, the political system, the legal framework, etc.

1.1 Construction of the model: Fundamental concepts and parameters

The model is designed in order to reflect a civilization as an evolutionary system that increases its (social) complexity by binding an increasing amount of free-energy. Within this framework the model's concepts and parameters constitute a general classification of a civilization's norms to manage free-energy.

1.1.1 The Energy Paradigm

The modelling of a civilization's energy macrodynamics, concerns very long time periods; the "energy paradigm" periods, which usually last from decades to centuries. The "energy paradigm" is a civilization's dominant pattern of energy harvesting. The energy history of human civilizations may be described shortly as the successive transition from one energy paradigm to another. For example, hunter-gatherer civilizations were based on human-muscles energy. Their natural successors were the first agricultural civilizations based on crop energy, and so on. An energy paradigm period is generally distinguished in three periods; "Formation", "Acceleration" and "Saturation". The first period concerns the self-organization of the norms regulating the energy paradigm and is usually a product of social ferments. The acceleration period concerns its rapid adoption, while the third its saturation because of resource depletion. Energy paradigms are initiated by an *event of structural change* which usually manifests intensively near the saturation period, but not spontaneously. Contrarily, it is the result of very long term social ferments that start to work from the very beginning of each energy paradigm. Structural change events constitute the factors that trigger energy transitions throughout human history. The most current example of structural change was the Industrial Revolution, which ignited the – until today- fossil fuelled civilization.

1.1.2 The Energy Scale

The energy scale is a core concept concerning the real fuel wealth of a civilization's energy paradigm. It is actually the mathematical integration of three key factors in the model: **(a)** the size of nominal free-energy (exergy) reserves **(b)** the energy demand and **(c)** the substitution ratio by a new energy source or technology. Nominal free-energy reserves concern the size of the deposit of available free energy. Their study provides us with much initial information. A civilization with rich free-energy deposits is generally expected to grow more, faster and more easily. However, this fills only a part of the picture. Complementary to that is the demand to use a part of that deposit. This is the civilization's marginal propensity to consume the deposit. Demand constitutes the primary denominator of the nominal energy reserve. Rapid increases in energy demand are expected to deplete proportionally rapidly the nominal reserve even when that's rich. A counter factor and exergy deposit re-nominator is substitution¹. When society discovers and adopts new energy sources, it actually substitutes traditional deposits with the new ones. Demand for these new deposits actually abstracts demand from traditional ones, thus slowing down the consumption/deposit ratio. Generally, high substitution ratios constitute a "technological compensation" for the rapid depletion of the reserve, while low ratios may even intensify it.

1.1.3 Parameter analysis

Based on the above assumptions we may formulate the dynamics of an energy paradigm as a function of these three parameters, presented below:

$$E_t = \varepsilon_t E_{t-1} - \frac{(1 - \alpha_t) \cdot \varepsilon_t}{A_t} E_{t-1}^2, \quad (1)$$

Where, $E_t > 0$, $A_{t-1} > \varepsilon_t > 1$, and $0 \leq \alpha_t \leq 1$

We may also write the above equation in a form of a differential equation:

$$E_t = \left(\frac{d\varepsilon}{dt} \right) E_{t-1} - \frac{\left(1 - \frac{d\alpha}{dt} \right) \cdot \left(\frac{d\varepsilon}{dt} \right)}{\left(\frac{dA}{dt} \right)} E_{t-1}^2 \quad (2)$$

The ratios between the parameters ε , α and A will define the model's dynamics such as the slope, the maximum value, the time of saturation and the smooth or extremely oscillating adjustments around a peak value. In the very long period –as assumed- the parameters are variables. Parameter A is the capacity parameter, which in real terms is the richness of the free-energy deposit (such as fuel density, number of natural deposits in a geographical area, energy efficiency increases, etc.). This is variable because in the very long period new discoveries, increases in energy efficiency or expansion in territories with rich deposits may increase its availability. Parameters ε and α , are two antagonistic coefficients that reflect the two opposing propensities in the energy use pattern. The one is conceived as a factor that tends to increase energy use (such as population increase, cheap access to fossil fuels, massive construction plans etc.) and the other as a factor that tends to abate it (such as the R&D of new materials and new energy sources). Parameter α is the free-energy substitution coefficient. This is the "evolutionary" part of the

¹ Substitution here is considered as "Innovation". Innovation is a far different term from "technical improvement". Technical improvements aim to increase the energy efficiency of the existing energy paradigm. Innovation refers to a shift in the society's technical infrastructure that is usually substituting the former one. Innovation initiates a new "energy paradigm". The same distinction between "improvement" and "innovation" is also made by Anghion & Howitt [Anghion & Howitt, 1998].

equation and constitutes an indicator of the civilization's energy transition intensity. In 2008, the fossil fuels' share in total primary energy supply (TPES) was estimated to be near 74% [IEA, 2010]; thus, giving a parameter α value around 0,26. Since substitution actually removes a part of the energy demand from the paradigm and transfers it to other energy sources, the parameter shows with what intensity that happens. In that way substitution works as a control mechanism.

1.1.4 Parameter feedback loops

It is also assumed that there are causal relationships between certain combinations of parameters A , ε and α . It is actually the result of such feedbacks between the parameters that defines the overall behaviour of a non-linear model [Meadows et al, 1972]. Figure 1.1 presents all combinations of positive and negative feedback loops:

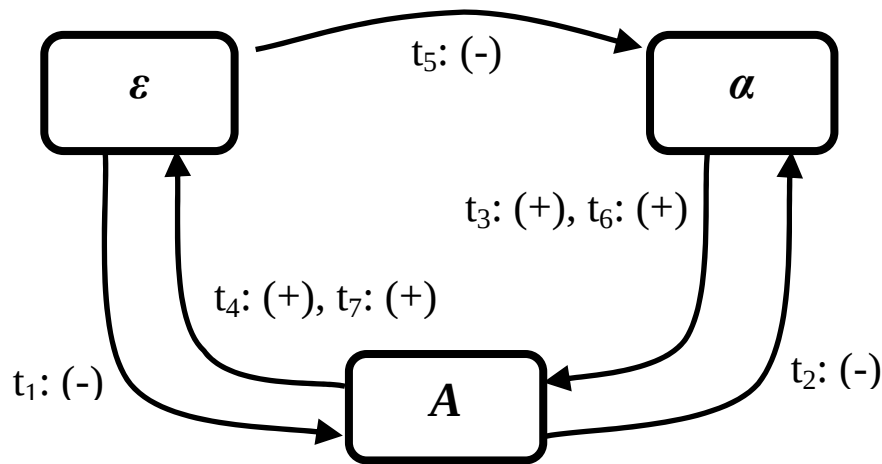


Figure 1.1. The complete circuit of seven successive periods of positive and negative feedback loops between the model's parameters

The above figure presents the feedback loops as a circuit that completes a full feedback cycle after seven successive (7) periods. According to the figure, the feedback loops are distinguished between negative and positive, according to the correlation between the parameter pairs. For example, the demand (ε) and deposit (A) parameters are negatively correlated, since as the demand increases the deposit runs out.

The complete feedback loop cycle goes as following: For a given deposit A there is a fuel demand ε , which diminishes the deposit (t_1). The depletion of the deposit activates the substitution mechanism (t_2), by a percent equal to α . Substitution (suppose there is no time hysteresis) partially re-nominates the deposit (t_3), since it actually works as fuel conservation mechanism. The increased deposit motivates a growth in the demand (t_4) that causes a crowding out of the substitution effect (t_5), since through the increased demand the energy paradigm regains a part of its initial share in total energy use. The displaced substitution effect gives the message of a reduced deposit again (t_6) that regulates demand in the last period (t_7).

The parameters should be considered to consist of an autonomous part (assumed to stand before t_1) and a differential part (from t_1 and on). If all relations between the parameters are expressed according to Figure 1.1, the model takes the following differential form:

$$E_t = \left(\frac{\left(\varepsilon + \varepsilon \cdot \frac{dA}{d\alpha} \right)}{dt} \right) \cdot E_{t-1} - \frac{\left(1 - \frac{\left(\alpha + \alpha \cdot \frac{dA}{d\varepsilon} \right)}{dt} \right) \cdot \left(\frac{\left(\varepsilon + \varepsilon \cdot \frac{dA}{d\alpha} \right)}{dt} \right)}{\left(\frac{\left(A + A \cdot \frac{d\alpha}{d\varepsilon} \right)}{dt} \right)} \cdot E_{t-1}^2 \quad (3)$$

As said, a civilization is a system evolving its energy harvesting patterns under the pressure of resource depletion. In order to activate the substitution process it must be able to incorporate the information on the deposit's depletion. The faster the information flow, the faster is the substitution; thus, the overall transition process (less time hysteresis). The substitution parameter (α) has exactly that role; it endogenously incorporates -most of all parameters- the civilization's ability to make a transition to more abundant energy sources.

1.2 Energy Paradigm dynamics

The overall energy dynamics are determined by ratios of the model's parameters. The primary condition of stabilization is where the energy use of two successive periods is equal:

$$\varepsilon_t E_{t-1} - \frac{(1 - \alpha_t) \cdot \varepsilon_t}{A_t} E_{t-1}^2 = E_t \Rightarrow (\varepsilon_t - 1) E_t \left(1 - \frac{\left(\frac{(1 - \alpha_t) \cdot \varepsilon_t}{A_t} \right)}{\varepsilon_t - 1} E_t \right) = 0 \quad (4)$$

According to (4) equality of $E_{t-1} = E_t$, stands for $\varepsilon_t = 1$, $E_t = 0$ and for

$$E_t = \left(\frac{\varepsilon_t - 1}{\left(\frac{(1 - \alpha_t) \cdot \varepsilon_t}{A_t} \right)} \right) \quad (5)$$

It is obvious that according to (1) only the third condition may be accepted. The energy use curve reaches its maximum value where the first derivative is zero:

$$\frac{\partial f}{\partial E_t} = 0 \Rightarrow f'(E_t) = 0 \Rightarrow \varepsilon_t - \frac{(1 - \alpha_t) \cdot 2\varepsilon_t}{A_t} E_{t-1} = 0 \quad (6)$$

Based on (6) the maximum energy use level is for:

$$E_{t-1} = \frac{1}{2} \cdot \left(\frac{\varepsilon_t}{\left(\frac{(1 - \alpha_t) \cdot \varepsilon_t}{A_t} \right)} \right) = \frac{A_t}{2 \cdot (1 - \alpha_t)} \quad (7)$$

Relation (7) is the most important, because it defines the maximum amplitude of the energy scale, expressed as a function of the deposit and the substitution ratio. The earlier that maximum value is reached, the sooner a civilization has to make the necessary transition to a new energy paradigm otherwise it faces energy shortages and gradual collapse. Assuming that substitution is zero, the maximum value is reached when the deposit is exactly half of the initial amount. This is the maximum possible remaining deposit at which the energy scale amplitude maximizes. For non-zero substitution ratios this amount increases proportionally, since every substitution unit makes the remaining reserve less restrictive. Figure 1.2 is indicative of the above relations.

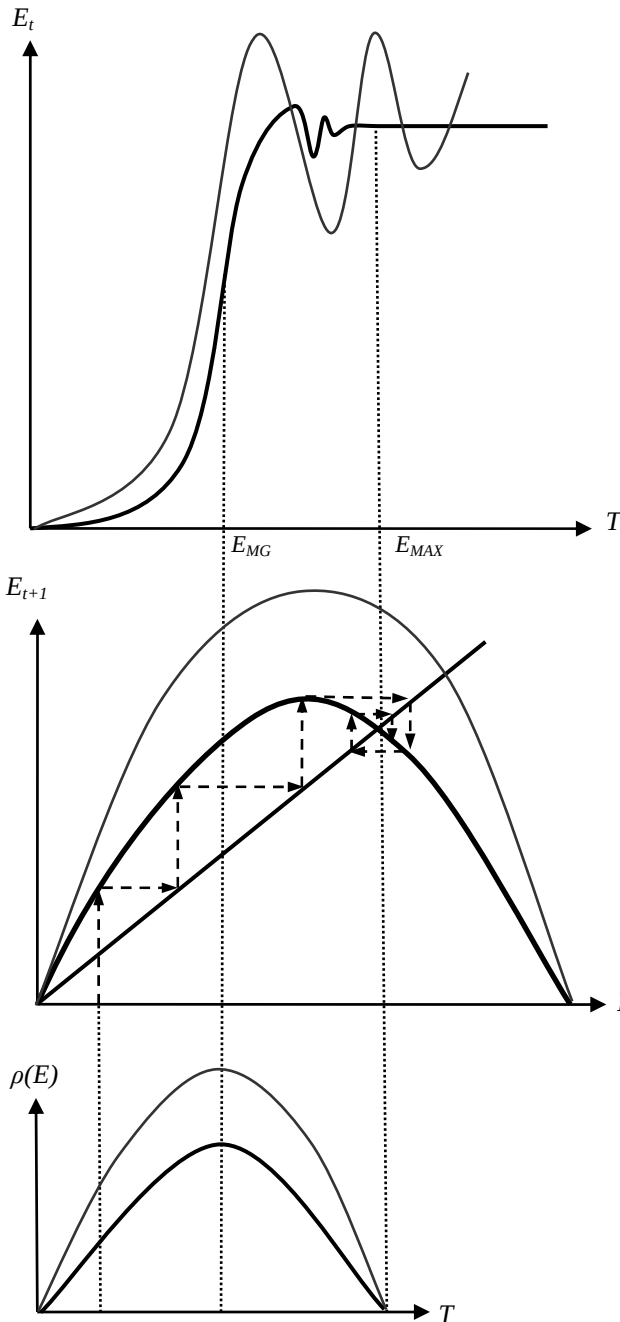
The influence of energy demand growth (ε) to the overall energy curve dynamics is also very significant. This is shown indirectly in relation (7) through the deposit parameter (A), of which the amount -according to figure 1.1- depends on the energy demand growth. Relation (7) shows at what level the energy scale reaches its maximum value, but does not show how soon will that be. This depends by the demand parameter ε . Overestimation of the energy scale margin may lead to over-consumption and cause significant oscillations with a final result the civilization's energy default, since the necessary minimum energy flows for its maintenance will no longer be available. In Figure 1.2 two cases are exemplified; one where the energy use curve stabilises after a small succession of oscillations (black curve) and a case of perpetually oscillating and not balancing at all (dark grey curve).

The first part of the diagram is the familiar logistic function curve presenting the energy paradigm by separating it to its constituent periods (Formation, Acceleration and Saturation). A significant attribute of that part is the steepness of the slope that shows the society's substitution flexibility (big value of α) or its addiction to the energy paradigm (α is always very small or zero). This part is constructed based on the dynamics governing the other two parts. The second part presents the relative evolution of energy use between two successive periods. In this part the 45° line expresses all the points where the output value of a certain period is used as an input value for the successive period. From that curve derives the conclusion that the ratios between the parameters have a significant impact on the possible oscillations of the logistic function curve. Where the line and the curve meet is the value of stabilization of the energy curve.

For this value there is an optimal ratio between the two parameters so that the deposit is fully consumed (utilized), while no oscillations precede stabilization. Any deviations from that optimal point will either leave a part of the deposit unutilized or lead to an oscillating curve. Diagrammatically, this point is optimal when located where the 45° line meets the parabolic curve at its peak. According to (1) and (7):

$$E_t = \varepsilon_t \left(\frac{A_t}{2 \cdot (1 - \alpha_t)} \right) - \frac{(1 - \alpha_t) \cdot \varepsilon_t}{A_t} \left(\frac{A_t}{2 \cdot (1 - \alpha_t)} \right)^2 = \frac{\varepsilon_t \cdot A_t \cdot (2 - A_t)}{4 \cdot (1 - \alpha_t)} \quad (8)$$

Relation (8) is the condition for the optimal ratio between the parameters all along the curve. This ratio is of extreme importance because since all parameters are variables, its preservation must constitute a social target for the conduction of long-term energy policy. Deviations below that peak form an energy scale below the maximum potential but allow it to function at that level for more than one period. Values exactly at the peak form the energy scale at its maximum potential, but this point is unique; which means that it can function for only one period. After that the curve starts to decline and society must have made the transition, otherwise it is about to face increasing shortages leading it gradually to energy default. In contrast, deviations above that peak will cause oscillations around a central value –smaller or bigger- depending on the size of the deviation. The bigger is the deviation of the curve's peak from the line, the more oscillating is the logistic function curve. The extreme case is where the peak deviates so much from the line that the input value leads to a zero value at the next period. This is translated as an extremely high ratio between parameters ε and α . The third part presents the growth rate of demand per unit



The stabilization of the curve at a certain level, depends on the achievement of an optimal ratio between the parameters ε , α and A . Both the level and the time of reaching it depend on that ratio. Steepness of the slope shows that society either does not substitute its energy paradigm (α is always very small or zero) or its demand is inflexible in substitution increases. Such a curve ends up oscillating, showing a civilization addicted to its energy paradigm.

This curve is designed to present the energy use between successive periods. Its slope and peak are defined by the ratio between ε , α and A . Large values of ε may cause extreme oscillations, while large values of α and A , a very low energy use level leaving a part of the deposit unutilized. The optimal deposit utilization is where the 45° line meets the peak of the curve.

The $\rho(E)$ is a differential function expressing the energy use growth ratio (thus deposit depletion) as an integration of ε , α and A . Its peak shows the *Maximum Energy Use Growth Ratio* (E_{MG}). For changes in any of the parameters, the whole function –thus the shape of the curve– changes as well.

Figure 1.2. An overall view of a civilization's curve of energy macrodynamics

time from the beginning of the paradigm until its end, taking into consideration the combined effect of all the parameters; thus it measures the real demand growth. Its peak shows the maximum growth ratio, which is presented at the second part as the maximum distance between the 45° line and the curve.

2. ENERGY PARADIGM SUBSTITUTION: CONTROLLING THE ENERGY SCALE

Fuel substitution is a kind of energy investment. As shown in (7), substitution can easily be used as a mechanism of regulating the restrictions of the energy scale (as it is R&D intensive). A substitution increase by one unit will increase the total limits of the

energy scale; thus making every unit of exergy used less restrictive than before substitution.

2.1 Substitution as an “energy scale multiplier”

Increases in substitution actually work as an Energy Scale Multiplier (ESM). The ESM is *the amount of the additional available exergy units per unit of increase in substitution*. In a few words the ESM calculates the increase of the energy scale because of an increase in substitution. The ESM may be formulated as:

$$ESM = \frac{1}{\left(\frac{(1-\alpha) \cdot \varepsilon}{A} \right)} E_{\max} \quad (9)$$

For as long as society substitutes its current energy paradigm, it increases its margins. In order to calculate the total increase in the energy scale is necessary to assume constancy in the other two parameters (*ceteris paribus*) for that specific period, so that the upper limit of the current energy scale is calculated ($E_{\max}$).

2.2 Crowding out energy paradigm substitutions

Significant increases of the energy scale are usually not the case. As said, in the long term, demand is considered to be variable. In that case, substitution increases are perceived as an opportunity to increase energy use. This will neutralize -partially or completely- the initial multiplier effect. Figure 2.1 is indicative of such a case:

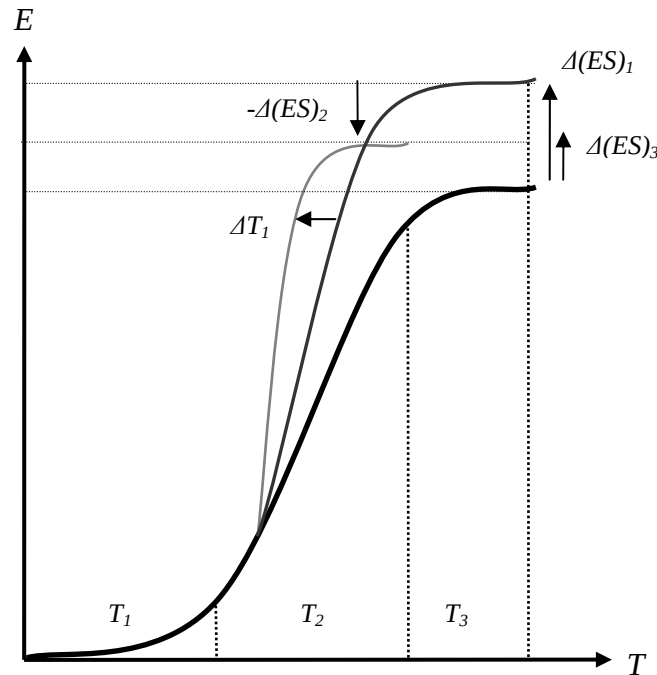


Figure 2.1. Display of the ESM and substitution crowding out mechanism

An initial increase in the energy efficiency will multiply the energy scale [$\Delta(ES)_1$, dark gray curve]. This effect does not change the initial structure of the paradigm’s life-time T (separated in T_1 , T_2 , and T_3) and also allows an increase in energy demand. However, if society has a very high propensity to increase demand for every substitution increase, the former effect will be partially crowded out [$-\Delta(ES)_2$] leaving a net positive effect [$\Delta(ES)_3$,

light gray curve], but smaller than the initial one. The increase of the energy demand coefficient also results to faster consumption ratio of the deposit (light gray curve).

Under these conditions the new energy scale is expected to stabilize in a lower level, of which its limits will be reached in a shorter time. However, the size of this “crowding-out” effect depends on the sensitivity of energy demand to substitution increases. An over-sensitive demand may even reduce the energy scale to a lower level compared to the one before the increase. This would be an overestimation of the importance of the substitution increase. That is why it constitutes only a temporary “compensation” for the rapid depletion of the reserve caused by increased demand.

Therefore, the real increase of the energy scale includes the crowding-out effect as:

$$ESM = \frac{1}{\left(\frac{(1-\alpha) \cdot \varepsilon \cdot \left(1 + \frac{d\varepsilon}{d\alpha} \right)}{A} \right)} E_{\max} \quad (10)$$

The above formula is the differential form of ESM. For simplicity it is assumed that there is no time hysteresis in the demand response. The elasticity β of energy demand to substitution increases is:

$$\beta = \left(\frac{d\varepsilon}{d\alpha} \right) \cdot \left(\frac{\alpha}{\varepsilon} \right) \quad (11)$$

The elasticity provides a better picture of the response of demand in substitution increases because it measures it as a percentage by removing all the differences of scale of magnitude between the two parameters. The calculation of all the substitution elasticity differentials as an integer for a specific time-frame, provides the net substitution effect; negative (substitution) or positive (crowding-out). Hence, the primary condition for a civilization’s energy transition to be complete by a specific time limit is:

$$\int_0^T \beta dt = 0 \quad (12)$$

Primarily, the integer may be negative in order to be consistent to the negative correlation between ε and α , described in figure 1.1, although after a value of $\alpha > 0,5$ the correlation may become positive because the share of the new energy source is high enough that it becomes the new energy paradigm (dominant pattern of energy harvesting). In that case, it is quite probable that it enters to the phase of its massive adoption, which means that the old paradigm is massively abandoned. The closer the integer is to zero the bigger the net substitution effect. If the integer is equal to zero the energy paradigm has been substituted completely. Contrarily, if the integer is equal to -1, there is no net substitution effect at all; it has been crowded-out by energy demand increases. In the extreme case where the integer is smaller than -1, there is a negative substitution effect, which means that not only substitution was completely crowded-out, but the demand was so sensitive against substitution increases, that there was a net demand growth on the current energy paradigm. The size of this net growth depends on the value of relation (12). For example, a value of -2 would mean that –on average- for every substitution of one unit the demand was doubling. This would reflect a civilization extremely addicted to its current energy paradigm with complete inability to make a transition. It reveals significant structural anchyloses preventing society from making an

energy transition, decreasing in this way its probability of survival. This actually concerns our fossil fueled civilization as well. Civilizations like the one described are not expected to survive beyond the time limit of their current energy paradigm.

CONCLUSIONS

This paper conceives human civilizations as dynamic ecosystems with energy budgets and develops a macrodynamic model in order to outline their evolution in time. Fundamental concept to that model is the “energy paradigm” can be considered as the humanity’s dominant pattern of energy harvesting. The model is assumed to follow logistic function dynamics with three integrated parameters that reflect the civilization’s internal structure and “free-energy metabolism”; thus determining its real fuel wealth or energy scale.

The ratios between the parameters are proven to be of vital importance, since they define the attributes of the energy use curve; thus the civilization’s energy dynamics. The parameter analysis concerns various aspects, all converging to the issue of securing the civilization from extreme oscillations in energy availability. Further research challenges concern the model’s enrichment with econometric data that will provide more solid proof of it’s consistency with the theory of cultural evolutionism.

REFERENCES

- Anghion, Philippe & Peter Howitt (1998), *Endogenous Growth Theory*, MIT Press
- British Petroleum (2010), *BP Statistical Review of World Energy 2010*, www.bp.com
- Holing, C.S. (2009), “Will the Twain ever meet when Ecosystem Theory focuses on instability (Resilience) and Macroeconomics focuses on stability (Efficiency)?”, lecture from the *Canadian Society’s for Ecological Economics (CANSEE) 8th Biennial Conference, “Prosperity for a Sustainable Society”*, Vancouver, Canada
- International Energy Agency (2010), *Key World Energy Statistics 2010*, IEA
- International Energy Agency (2008), *World Energy Outlook 2007: China and India Insights*, IEA
- Meadows Donella, Meadows Lennis, Randers Jorgen, Behrens III W. William (1972), *The Limits to Growth: A Report for the Club of Rome’s Project on the Predicament of Mankind*, Universe Books
- Odum, Howard T. (2002), *Environment, Power & Society for the 21st Century: The Hierarchy of Energy*, Columbia University Press
- Odum, William E., Eugene P. and Howard T. (1995), “Nature’s Pulsing Paradigm”, *Estuaries and Coasts*, Vol. 18, no 4
- Odum, Howard T. (1971), *Environment, Power & Society*, John Wiley & Sons
- Smil, Vaclav (1994), *Energy in World History*, Westview Press
- Tainter, Joseph (1988), *The Collapse of Complex Societies*, Cambridge University Press
- Wall, Goran (2005), “Exergy Capital and Sustainable Development”, *Proceedings of the Second International Exergy, Energy and Environment Symposium, Kos, Greece*, Paper No. XII-I49
- White, Leslie (1959), *The Evolution of Culture: The Development of Civilization to the Fall of Rome*, McGraw-Hill.

A ROBUSTNESS EXERCISE ON THE EKC FOR CO₂ EMISSIONS

Tommaso Luzzati^{*1} and Marco Orsini²

¹ *Dipartimento di Scienze Economiche, Facoltà di Economia, Università di Pisa, v. Ridolfi 10, I-56124 Pisa – ITALY*

² *Institut d'Etude et des Conseils en Développement Durable (ICEDD), Bd. F.Orban 4, BE-5000 Namur, Belgium*

ABSTRACT

This paper re-examines the environmental Kuznets curve (EKC) for CO₂ emissions. In order to adhere to the EKC story, CO₂ emissions are taken in absolute rather than in per capita terms. We employ both parametric and semi-parametric methods. Our dataset includes 142 countries for the period 1971-2007. The robustness of cross-country analysis is checked first by focusing on a sub-sample which excludes potential outliers, and then by looking both at the world as a whole and at country patterns. Our findings confirm the importance of robustness exercises, supporting the idea that the evidence in favour of a CO₂-EKC, if any, is a statistical artefact.

Keywords: Environmental Kuznets Curve, CO₂, semi-parametric estimates, robustness

1. INTRODUCTION

The environmental Kuznets curve (EKC) debate, which started in the 1990s and is still very much alive, has produced mixed results. This is due both to the multifaceted nature of the issue and to the research strategies adopted. Indeed, criticism has often been levelled at the scant attention paid to robustness (for a thorough survey on the EKC see Stern, 2004). Several facets of robustness have been investigated, for instance by applying non-parametric methods (e.g. Bertinelli and Strobl, 2005; Azomahou et al., 2006), by comparing alternative datasets and different parametric setups (Galeotti et al., 2006a), and by testing for series stationarity (Galeotti et al., 2006b).

Our robustness exercise involves both comparison between parametric and non-parametric methods, and the validation of cross-country findings by looking at other levels of analysis (i.e. the world as a single country and individual countries). This should mitigate the risk of statistical artefacts arising from pooling heterogeneous country patterns.

Another innovative element is that we take emissions in absolute rather than per capita terms. This is required for empirical analysis to be consistent with the EKC hypothesis, “an inverted U-shape relation between environmental degradation and income per capita (Stern 1998, 173)” according to which “higher levels of development [...] will result in levelling off and gradual decline of environmental degradation” (Panayotou, 1993, 1). While theoretical contributions (see Aghion and Howitt, 1998, 151-171; Brock and Taylor, 2005) consider environmental degradation in absolute terms, the empirical EKC literature has focused on per capita terms. However, as far as ‘Nature’ is concerned, what matters is **total** human pressure and not **per capita** pressure.

Following the literature, we investigate here a reduced form in which only per capita income is taken as ‘explanatory’ variable; in other words, we do not seek the determinants

* Corresponding author; E-mail: tluzzati@ec.unipi.it; Tel. ++39-050-2216329

of anthropogenic environmental pressures, which would entail modelling the structural linkages explicitly. Convincing reasons for considering only per capita income are provided, for instance, by Azomahou et al. (2006,1348). We apply our exercise to CO₂ emissions, one of the most widely studied indicators¹.

2. CROSS-COUNTRY EVIDENCE

2.1 Data and methods

Our data, depicted in figure 1, consist of annual observations of CO₂ and per capita GDP (constant 2000 \$ PPP) for the period 1971-2007 and for 142 countries². The source is IEA. (see Figure 1).

Cross-country data are investigated by using both non-parametric and parametric methods. We follow a standard EKC regression model,

$$CO_{2it} = \alpha_i + g(percapitaGDP_{it}) + \varepsilon_{it} \quad (1)$$

where country-specific intercepts α_i capture differences that are independent of income. We take variables in natural logarithms. As usual, $g(\cdot)$ was set identical for all countries. We also investigate the implications of including a linear trend in (1).

In order not to force data into a specific frame, we start from a non-parametric approach that allows $g(\cdot)$ to be a smooth and continuous (possibly non-linear) function of the regressors. This is particularly important since the existence of a turning point is crucial. We perform a semi-parametric regression and fit the data with a Generalized Additive Model. We use the routines contained in the MGCV package for R (Wood 2006). Since standard diagnostics do not apply, the package provides estimated Bayesian confidence intervals for the non-linear term.

Parametric analysis is performed by using a cubic specification for $g(\cdot)$, which is standard in the EKC-debate. The dummy variables α_i can be taken either as fixed or random effects. A Hausman test allows checking for inconsistency in the random effects estimate. Autocorrelation and heteroskedasticity are checked respectively by the test discussed in Wooldridge (2002,282) and by a likelihood ratio test. We also look at the issue of series stationarity³ by running the tests developed by Levin, Lin and Chu (2002) and by Im, Pesaran, and Shin (2003).

¹ It has to be noticed that CO₂ is not a wide encompassing indicator for anthropogenic pressures on the environment. For instance CO₂ emissions can be reduced by increasing nuclear power which involves, however, other well-known drawbacks.

² Canada, Mexico, United States, Australia, Japan, Korea, New Zealand, Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, Algeria, Angola, Benin, Botswana, Cameroon, Congo, Dem. Rep. of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libyan Arab Jamahiriya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, United Rep. of Tanzania, Togo, Tunisia, Zambia, Zimbabwe, Other Africa, Bahrain, Islamic Rep. of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen, Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Gibraltar, FYR of Macedonia, Malta, Romania, Serbia, Slovenia, Former Yugoslavia, Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Former Soviet Union, Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela, Other Latin America, Bangladesh, Brunei Darussalam, Cambodia, Chinese Taipei, India, Indonesia, DPR of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Thailand, Vietnam, Other Asia, People's Rep. of China, Hong Kong

³The issue entered the EKC debate after criticism raised by Stern (1998)

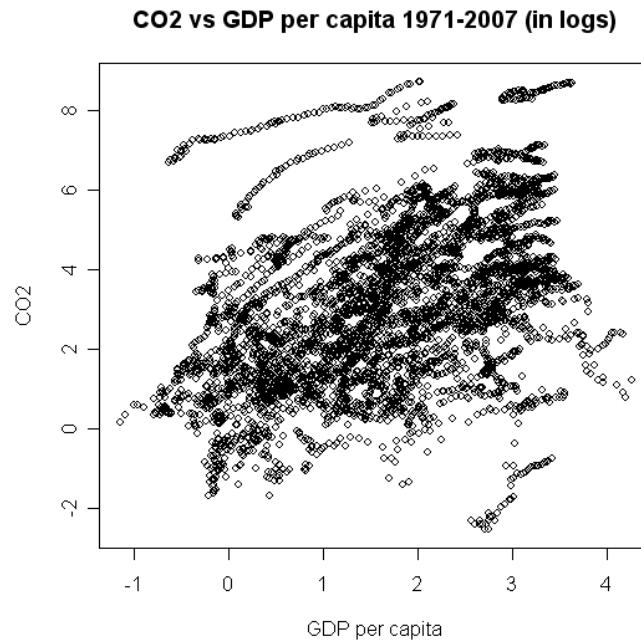


Figure 1. The dataset

2.2 Results

Non-parametric estimates

Figure 2 shows our semi-parametric fit and confidence band (5%). The curve actually shows a turning point, at about 27,500 \$2000PPP.

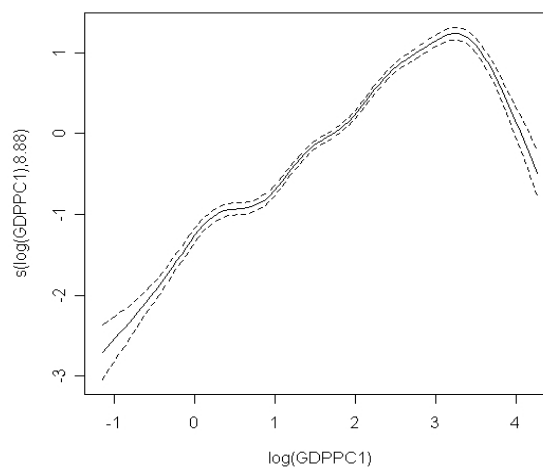


Figure 2. Semi-parametric regression of CO₂ on GDP p.c. all countries

Studies on the EKC often include a time trend in the regression. Figure 3 shows the semi-parametric estimates when including time. Its effect on CO₂ is positive and the turning point becomes sensibly lower, at about \$15,000.

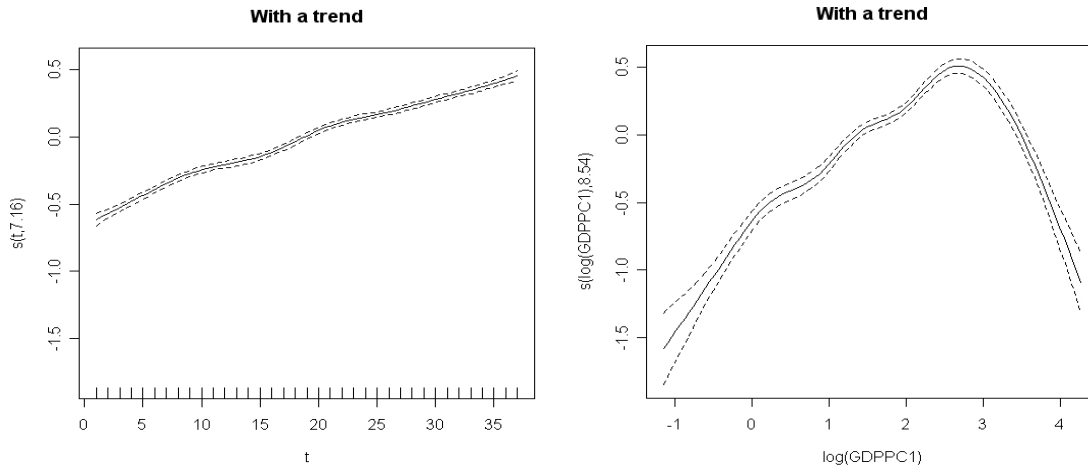


Figure 3. Semi-parametric regression of CO₂ on GDP p.c. with time trend

We then restricted our database to 99 countries. We excluded very peculiar countries (e.g. “oil” economies) since it is implausible that other countries can follow similar patterns, and very small countries to avoid their pattern to affect the overall estimate disproportionately. We also grouped together all countries respectively of the former Soviet Union and of the former Yugoslavia.⁴ The estimate in figure 4 shows that the EKC does not hold for the new, and more reasonable, database.

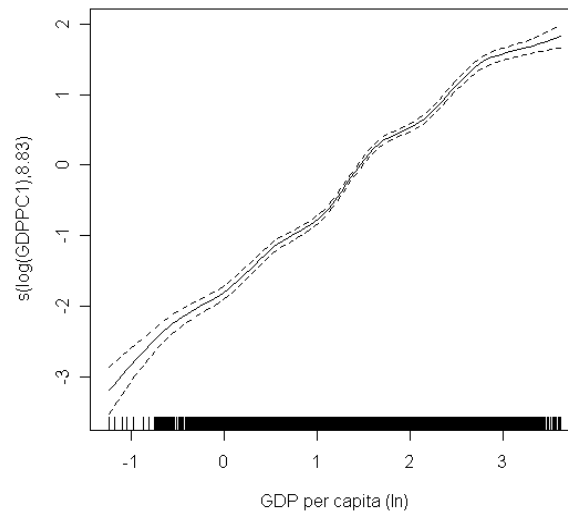


Figure 4. Semi-parametric regression of CO₂ on GDP p.c. 99 countries

Parametric estimates

Equation (1) is estimated as a random effect model after performing the Hausman test. The test for serial correlation suggests the existence of first order autocorrelation;

⁴Excluded countries are Iceland, Luxembourg, Botswana, Eritrea, Libyan Arab Jamahiriya, Namibia, Other Africa, Bahrain, Iraq, Kuwait, Oman, Qatar, Saudi Arabia, United Arab Emirates, Bosnia and Herzegovina, Croatia, Cyprus, Gibraltar, FYR of Macedonia, Malta, Serbia, Slovenia, Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan, Netherlands Antilles, Other Latin America, Brunei Darussalam, Cambodia, Chinese Taipei, Mongolia, Other Asia.

heteroskedasticity is detected by the likelihood ratio test. Thus, we fit our model by using feasible generalized least squares (FGLS). The estimate is as follows (Table 1).

Table 1. Parametric estimate (FGLS) of the CO₂-EKC

2010	Coeff.	Std. Error
ln GDP/P	0.68	0.049
(ln GDP/P) ²	0.27	0.036
(ln GDP/P) ³	-0.076	0.0068
turning point	≈ 26,500 \$2000PPP	

When adding a deterministic trend, diagnostics suggest using FGLS again. Time coefficient is positive (0.016, std.err.=0.001). As in the semi-parametric analysis the shape does not change, while the turning point becomes lower. Adding a trend would be consistent with the test by Levin, Lin and Chu⁵ that suggests stationarity for CO₂ and GDPpc, trend stationarity for squared and cubed GDPpc. Finally, we check⁶ for group differences by pooling countries according to their income: low (<\$3,000), middle (\$3,000-\$10,000), and high(>\$10,000). We run parametric regressions after including dummy variables to allow for different coefficients. This specification yields estimates that are consistent with the semi-parametric results.

3. INDIVIDUAL PATTERNS

3.1 The world as a single unit

Since the beginning of the EKC debate (Grossman and Krueger, 1991), the relationship between rich and poor countries has been held as crucial due to the presence of two countervailing forces, transfer of cleaner technologies and “environmental displacement”; when looking at the world as a whole such effects are neutralised. Figure 5 shows the picture at the world level.

The lack of any evidence for an inverted-U relationship is so clear that there is no need for any econometrics. Nonetheless we performed some co integration analysis⁷. Given some evidence of the series to be integrated of order 1, we found that the best fit of the data is the following cointegrating regression (all variables are in natural logarithms):

$$CO_2 = -1.392 + 1.2929 \times GDPpc + D7181 \times 0.027 + D9107 \times 20.639 - D91\_07 \times 0.72836 \times GDPpc^2 + D91\_07 \times 0.05247 \times GDPpc^3$$

Daa_bb is a shift dummy from year ‘aa’ to year ‘bb’

n=37, ADF(1) regression⁸: $\alpha_c = -4.47$, $p < 0.02$ (MacKinnon, 1996)

CO₂ and per capita income show a linear relationship for the period 1971-1990, with elasticity bigger than one, and a cubic one after 1991 (monotonically increasing). The intercept estimated for the period 1971-1981 is slightly lower in the next decade and rises sharply after 1990. The first structural break is consistent with the second oil shock, the second one with the break-up of communist regimes in Eastern Europe.⁹

⁵The test by Im, Pesaran and Shin discards trend stationarity of our series. For a discussion on differences in panel unit root tests see the survey by Caporale and Cerrato (2004).

⁶ Findings on request.

⁷ We followed Engle and Granger two stage method. Obviously we tested thoroughly our estimates. The results of all the tests are available on request.

⁸ The number of lagged difference terms in the ADF equations (number in brackets) was determined by minimizing the Aikake and Schwarz criterion and by checking the Breusch-Godfrey Serial Correlation LM Test.

⁹ When looking for the short run relationship, we got the following error correction model estimate:

$$CO2_t = -0.67 \times ect_{t-1} + 1.07 \times GDPpc_t - 0.73 \times GDPpc_{t-1} + 0.65 \times CO2_{t-1}$$

t-statistic: -3.15 8.99 -3.49 3.84

n=35, Adj.R²=0.76 *ect* = error correction term (residuals of the l.r. estimate)

An alternative regression, which seems to exhibit stationary residuals, suggests that also after 1991 a linear functional form can hold. If this is the case, after 1991 the elasticity (the estimated slope coefficient) would be less than one, about 0.85. New data will tell whether this is actually the case or, rather, the cubic relationship is valid¹⁰.

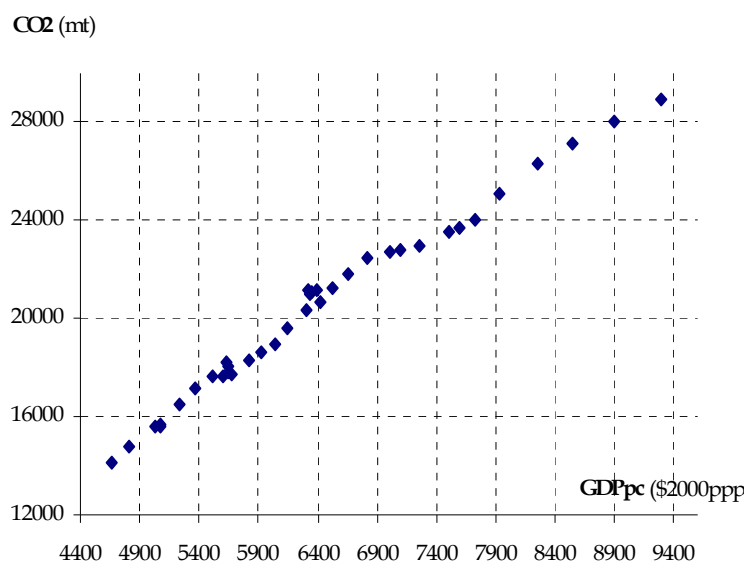


Figure 5. CO₂ versus income per capita (World)

For the sake of completeness, we followed the standard approach and used CO₂ in per capita terms. We found that the functional form estimated for total CO₂ can be used also for CO₂ p.c. to estimate a cointegrating regression¹¹ whose fit is shown in figure 6.

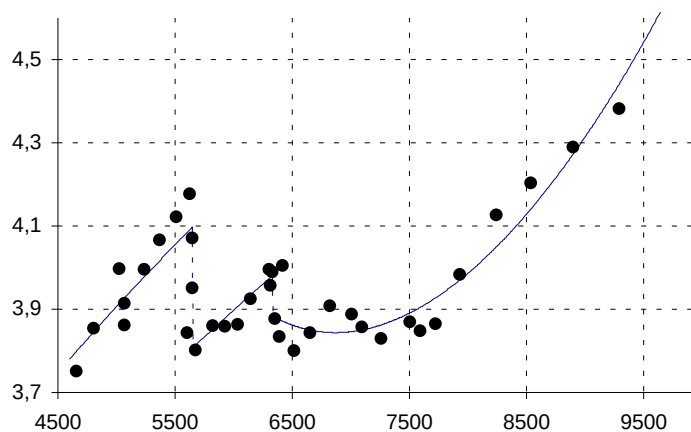


Figure 6. CO₂ per capita versus income per capita (World)

¹⁰ A quadratic form does not fit the data.

¹¹ $CO2pc = -2.058 + 0.393 \times GDPpc + D7181 \times 0.074 + D9107 \times 42.42 - D91\_07 \times 1.589 \times GDPpc^2 + D91\_07 \times 0.118 \times GDPpc^3$
 $n=37$, ADF(3) regression: $nc = -5.675$, $p < 0.01$ (MacKinnon, 1996)

3.2 Individual country analysis

To examine the issue at the country level is viewed as appropriate by several scholars, such as De Bruyn and Heintz (1999,671-672) and Stern et al. (1996,1159). Visual inspection of the scatter plots of income vs. CO₂ show (i) heterogeneity of patterns, (ii) few cases of inverted-U or decreasing curve¹². We also look at CO₂ average elasticities of income. To this end we first regressed CO₂ on per GPDpc (standard OLS, linear specification, logs) and then plot the estimated elasticities versus average GDPpc. This shows¹³ that elasticities are positive, albeit decreasing in per capita income; variability also decreases with income. This validates the findings of the cross-country approach.

4. CONCLUDING REMARKS

This paper looked for the CO₂ Kuznets curve by checking for consistency both at different levels of analysis and for different methods. A CO₂-EKC does not exist for the world as a whole and for most single countries. It shows up in the cross-country analysis if the dataset includes all countries for which data are available, which involves also including very peculiar outliers. Semiparametric methods offer a better fit of the data, while parametric methods underestimates the level of the turning point income, when this shows up.

Adding a deterministic trend lowers the turning point. However, time makes CO₂-emissions to increase, which is in conflict with the common findings that time, which is often interpreted as a proxy for technological progress (e.g. Shafik and Bandyopadhyay, 1992), reduces environmental pressures. Two reasons, however, suggest not including the trend. The first is that the EKC, in order to adhere to how its story is told, should be estimated by including only per capita GDP among the regressors. The second is that evidence of an EKC for CO₂ does not emerge either at the world or at single country level.

To sum up, we hope that our exercise contributed to the idea that a robustness check, at different levels of analysis and with different methods, helps reducing the perils of statistical artefacts implied in cross-country analysis.

REFERENCES

- Aghion P. and P. Howitt, 1998, *Endogenous Growth Theory* (MIT Press).
- Azomahou T., F. Laisney, and P. Nguyen Van, "Economic Development and CO2 Emissions: a Nonparametric Panel Approach", *Journal of Public Economics*, 2006, vol. 90(6-7), 1347-1363.
- Brock W. and S.M. Taylor, 2005, "Economic growth and the environment: a review of theory and empirics", in P. Aghion and S. Durlauf, eds., *Handbook of Economic Growth* (Elsevier).
- Bertinelli L. and E. Strobl, 2005, "The environmental Kuznets curve semi-parametrically revisited". *Economics Letters* 88, 350–357.
- Caporale G.M. and M. Cerrato, 2004, "Panel data tests of PPP. A critical overview", Institute for Advanced Studies Vienna, *Economics Series* 159, July
- de Bruyn S.M. and R.J. Heintz, 1999, "The Environmental Kuznets curve hypothesis", in J.C.J. Van den Bergh, ed., *Handbook of Environmental and Resource Economics* (Elgar) 656-677.
- Galeotti M., M. Manera, and A. Lanza, 2006a, "On the robustness checks of the environmental Kuznets curve", WP13, Università degli Studi di Milano.
- Galeotti M., A. Lanza, and F. Pauli, 2006b, "Reassessing the Environmental Kuznets Curve for CO2 emissions: a robustness exercise", *Ecological Economics* 57, 152-163.
- Grossman G.M. and A.B. Krueger, 1991, *Environmental impacts of a North American Free Trade Agreement*, NBER WP3914.
- Im K., H. Pesaran, and Y. Shin, 2003, "Testing for Unit Roots in Heterogeneous Panels", *Journal of Econometrics* 115, 53-74.

¹² About 10 countries, among which key examples are Germany, the UK and Sweden.

¹³ Findings on request.

- Levin A., C.F. Lin., and C.S. Chu, 2002, "Unit root tests in panel data: asymptotic and finite sample properties", *Journal of Econometrics* 108, 1-24.
- MacKinnon, J. G., 1996, "Numerical Distribution Functions for Unit Root and Cointegration Tests", *Journal of Applied Econometrics*, 11, pp. 601–618.
- Panayotou T., 1993, *Empirical tests and policy analysis of environmental degradation at different stages of economic development*, WP238, Technology and Environment Programme, ILO, Geneva.
- Shafik N. and S. Bandyopadhyay, 1992, *Economic growth and environmental quality: time series and cross-country evidence*. World Bank Policy Research, WPS 904, Washington, DC.
- Stern D.I., 1998, "Progress on the environmental Kuznets curve?", *Environment and Development Economics* 3, 175-198.
- Stern D.I., M.S. Common, and E.B. Barbier, 1996, "Economic growth and environmental degradation: the environmental Kuznets curve and sustainable development", *World Development* 24 (7), 1151-1160.
- Stern D.I., 2004, "The rise and fall of the environmental Kuznets curve", *World Development* 32(8), 1419-1439.
- Wood S.N., 2006, *Generalized Additive Models: An Introduction with R*. (CRC/Chapman&Hall).
- Wooldridge J.M., 2002, *Econometric Analysis of Cross Section and Panel Data* (MIT Press).

PROPOSAL FOR AN ANALYTICAL SIMILE FOR INTRA-EUROPEAN EXCHANGE OF MATTER-ENERGY. MANOILESCU – GEORGESCU-ROEGEN MODEL

Vasile Dogaru*

*Institute for Advanced Environmental Researches,
West University of Timisoara*

ABSTRACT

The choice measurement of general energy forms is possible using the framework proposed by Georgescu-Roegen. The operational measurement is possible by cost-price, using the theory of choice based on minimal effort, respecting properties of comparative advantage. A generalization of this principle, made by Manoilescu, assures the choice of objects containing forms of energy for large local communities (regions) of the EU-27, with verification and compliance of the general objective of regional convergence. The simile of the European economy on choice projection of concrete objects, taking into account energy consumption, ensures consistency of comparison with U.S. economy efficiency.

Keywords: Analytical simile of the European economy, Manoilescu, Georgescu-Roegen, comparative advantage, joint management of resources

1. GENERAL FRAMEWORK FOR MEASUREMENT OF MATTER-ENERGY EXCHANGE

The choice of an energy form is made related to matter (concrete objects) and a given technological process. According to Georgescu-Roegen (1979) „the energy (e) and matter in bulk (M) are not convertible into each other and there no relation $F(M, e) = \text{const.}$ In the choice process, Georgescu-Roegen assumes the case of two technologies (T), $T_1(M_0^1, e_1^1)$ and $T_2(M_0^2, e_1^2)$, producing the same result and such that $M_0^1 > M_0^2$, $e_1^1 < e_1^2$. Result can be defined as concrete object, a mix of energy and matter (to see the explanations bellow). Using the terrestrial resources, we do not have a unique solution, because the rational choice is „purely economic for it involves a multitude of factors of varying historical uncertainties and imponderabilities” (Georgescu-Roegen, 1979).

In the case of „free” solar energy, according to Georgescu-Roegen (1979), the choice must take into account net energy (NE), instead of gross energy. The choice between $T_1(M_0^1, NE_1)$ and $T_2(M_0^2, NE_2)$ when $M_0^1 > M_0^2$ and $NE^1 < NE^2$ is, also, an economic, not a purely technical problem. If $NE^1 = NE^2$, matter is decisive and T_2 is chosen, no matter (regardless) of the amount of gross energy used.

Georgescu-Roegen’s proposed scheme is not operational, strictly speaking, in the process of economic choice of objects, concrete forms of matter-energy. Georgescu-Roegen’s lesson about the limits of thermodynamic laws, formulated only for the energy and the suggestion to expand analysis for matter-energy is a return for Whole, within this duality, doubtless meaning only in analytical plan. On the market are still in the process of choosing only the most effective items, measured by the ratio of useful features–total manufacturing effort, so that other objects, having this report significantly diminished, will be waiting. The situation is the reverse of Gresham’s law in the currency area.

The choice of energy forms, related to matter-support, between various forms of its, goods and services within large communities – requires cooperation (von Mises, 1949)

* E-mail: vdogaru@feaa.uvt.ro; Tel: +40 256 592 570

and assigned a social criterion of supra-organic nature. This criterion encompasses the interests of existing communities and simultaneously individual self-interest one. The criterion can be supported by requirements of a real comparative advantage. It includes also, the general goal of economic and social processes, the enjoyment of life. In an attempt to use efficiently the matter-energy resources, the contrary interests of individuals, in economic and social processes, obviously may lose effort. This loss flagrantly violates the principle of minimum effort and is amplified at the aggregate level, through external adding. In the external aggregation, the technical efficiency decrease and it is explained by entropy of elementary processes. In a contrary situation, it is possible that the internal aggregation, with qualitative leap, in complex processes, to produce partial entropic compensation of subunitary efficiency ratio. This idea was not sufficiently analyzed by the scientists.

The slow increase of multifactor productivity in the last half century in the manufacturing sector (USDL, 1999) and of income increase in the last two decades in U.S. (Bureau of Census, 2002) emphasized that complex processes, organized most efficiently in manufacturing industry, are in a relative stagnation. A probable explanation is taking energy – higher imports, budget deficit in 60-70 decades – from other economic systems to decrease the own entropic deficit.²

Therefore, the operation of complex processes, that include human processes of economic-social sphere, fails, it seems generally, to contradict the evolution of the elementary processes, regarding the entropy reduction on longer periods. Thus, for complex processes, regarding the economic analysis of the roegenian Whole, is likely to fail to compensate the losses of these elementary processes due to the subunitary ratio of technical efficiency. A qualitative leap of elementary processes its components that are being added internally, issuing a new process and not a simple aggregation of elementary processes. Processes added internally (Georgescu-Roegen, 1971) are relatively few.

These losses occur due to weak links at the top aggregate level of the basic processes gathered outside. Such processes, which are the majority, are called the third degree phenomena. The study of some separate individuals – human being or nominal entity (company, by example) – or, contrary, at the maximum aggregate level (Georgescu-Roegen, 1971) – can not bring analytical solutions, being "out" of social science (Manoilescu, 1938).

Terrestrial forms of energy-matter, "visible" objects, can be considered in sufficient amount. The choice by individuals of one of these energy-matter forms facing many problems. The most important analytical issues refer to selected objects, by reducing them to *identical* objects, and adding energy-matter consumption, using a common measure for all (each) compared objects. Unit used is the currency.

This developed scheme covers the most possible situations, from barter exchange (Dogaru, 2000; 2006), with currency exchange, internal exchange, the relationship with the absolute advantage and other situations, trade costs and their influence in the calculation of comparative advantage. All these algorithms have been published during 2000-2005. Since Manoilescu's article from 1940 was not studied yet till recently, the scheme as proposed by the author has received just a few formal criticisms. Today there are identified some inconsistencies in his theoretical scheme, without reducing the value in itself of this discovery. On the contrary the scheme has new values by adding these proposed comments (Dogaru, 2010).

Some problems are artificially created in economic science. The distinction between costs and prices is not relevant, the transition between the two phenomena – are instant on the time arrow in economic processes. Manoilescu, who has solved some of the requirements of choice (on a qualitative level), avoided to give solution to relations between prices and costs because there were many debated problems. The rational choice in the production of goods, where there are limited stocks of resources, can be

² The cost instrument, which was used in the analysis of energy losses in the macro-social metabolic processes, will be justified below related to the price.

encouraged towards the use of other relatively abundant resources. The resources deplete relatively quickly and it requires finding of new recipes for mankind subsistence.

In fact, the choice identified by Georgescu-Roegen in the processes of consumption / production sets the general operational framework. At this socially complex level only the principle of minimum effort (of maximum efficiency) can be taken into account. Allegedly the choice is determined by at least two basic principles: the interest principle and the one cited above. The second principle it has also an anthropomorphic form. The first has as support the human selfish gene (Dulcan, 2008). Manoilescu (1938) makes an important distinction: social sciences, only deals with the study of human communities, but not of individuals, so the interest is only studied for large collectivities (regions, countries).³

2. AN ANALYTICAL SIMILE OF THE EUROPEAN EXCHANGE – SOME BASIC REQUIREMENTS

Building of analytical simile is strictly possible only for elementary processes and implies the acceptance of anthropomorphic rational choice to explain the evolution of these processes. The elementary processes of economic and social metabolic systems develop, usually, in contrary directions, so that their projection can be done only in stochastic manner (Georgescu-Roegen, in Szenberg, 1992).

At the aggregate level can be identified a weak rationality, valid for the large groups. The EU-27, by example, is considered a mix between different cultural matrix or behaviors. Because at the level of complex process we cannot speak about development (Florian, 1983), we can at least identify an evolution with an anthropomorphic purpose. Evolution meaning for development of human collectivities may be considered the maintaining and, in some extent, increasing of the social welfare, enjoyment of life. The evolution is currently measured in UE-27 at general level – by GDP/per capita or value added/per capita (Manoilescu, 1929) – in weak sense, which is the convergence objective. The explanation of evolution is useful to understand the entropy of elementary processes, and by aggregation (qualitative or quantitative), also at the level of complex systems. In these systems we have to prove entropy intensity based on behavior type and by social (weak or strong) relations. Quantitative measurement (by aggregation) of evolution in parallel with a qualitative index in the context of a regional collectivity, like measurement average individual income, assures a comparative observations and "delete" the qualitative leap – impossible to analyze in analytical science – from analysis and to emphasize errors of quantitative aggregation.⁴

In human collectivities the goods choice – having specific forms of energy and matter – in consumption / production may have as a reference point a Pareto (absolutely) optimum: all local collectivities gain in this exchange in a relative and absolute sense. The choice is observed, from an analytical perspective, in the most important social situations: the exchange of goods (energy and matter). This exchange measures the human consumption of energy-matter through cost-price, in the most refined way over time, using money. On the time axis the price will contain increasingly detailed external costs, including those from nature or asymmetric relations from direct exchanges between individuals.

Manoilescu (1938) exceed the classical analytical framework, including the neoclassic and has limited the validity of researches from economic science interest level of large communities, therefore in a qualitatively aggregation form (internally adding through qualitative leap) of the basic economic processes (Georgescu-Roegen, 1971). Manoilescu passes beyond of the analysis of the mutual advantages to analyse inside of elementary exchange process. Manoilescu has anticipated a more general solution,

³ We do not will take into account the dispute about what is collectivity or individual at elementary level – see (Florian, 1983).

⁴ To see the bilateral and multilateral index tests and the identity problem of compared objects, not of identical copies of the same object (Eatwell et al., 1988, *Index Numbers*).

issued before in a general shape by Georgescu-Roegen, to operating with resources of matter and energy. Regarding the choice analysis of specific objects in analytical plane, Manoilescu (1940) provides an amazing solution, being a forerunner of general framework provided by Georgescu-Roegen: $a : i < d$, where, a – ratio between agricultural product price (industrial country /with high income) and agricultural product price (agrarian country /with low income); i – ratio between industrial product price (industrial country /with high income) and industrial product price (agrarian country /with low income); d – disparity between labor productivity within agricultural country. In this case the agrarian country will be in comparative advantage to manufacture the industrial product.

The choice solution of goods, proposed originally by Smith-Ricardo-Torrens, refers strict only to fulfill requirements of individual selfishness of the entrepreneur and the consumer and partial to the rational choice, case in which the effort is minim. The rationality being defined and understood only at the social level (of community), the solution of classical economists for the individual exchange of energy and matter was incomplete. Manoilescu solution is significantly superior to the previous solution and with those currently offered because it analyzes the compromise between consumer-merchant relationship and the relationship between the communities located in different economic areas in the vicinity or in other remote areas. It simultaneously examines the two facets of exchange process (supply and offer).⁵ On the other hand, may be observed that selfish principle is a form (a case) of the minimum effort principle applies to human society.

This individual comparative advantage is founded, mainly, as gains from trade. The limit of analyse has become more obvious once with increasing of populations. In the current urban societies in which the number of individuals increased in the last two millennia more than 150 times (Maddison, 2001), the solution of individual choice is exceeded, even if we consider science as an analysis trough aggregation purely quantitative of comparative advantage of companies or the consumers, as reflected in some studies. Comparative advantage is external aggregate for purpose to calculate taxes and profit one. Georgescu-Roegen provides consumption analysis on the other end of the problem, identifying the need a joint management of resources. He brings as basic arguments in its proposals, the principles of thermodynamics in the physical world, partially explained from the anthropomorphic (social) point of view. He proposed, as noted, an extension of these principles to matter-substance. The current technological level and the resources stock ensure the existence of a population several times larger than today, but only inside of cooperative processes. Idea of supporting the individual comparative advantage rather than cooperation between large communities – see analysis on corporatism (Manoilescu, 1934) – has two limitations: a man is a selfish human being, so he will fight to climb on Maslow's pyramid.

The characteristic of selfishness is maintained in its original form from the human wild period, and is almost unchanged in the last 20 millennia (Dulcan, 2008). Therefore social exchanges has become necessary once with passing of human existence from tribes to the urban one, where the relations and requirements are numerous. The existence and, especially, maintaining of weak link between individuals in these relationships, which are similar to those in physics, is an evidence of analysis and of making decisions based on adding externally of elementary processes in an aggregate process (on the next level). The lack of cooperation stimulus, of economic activities strong related, is main general cause of current crisis. In addition, distorted analysis of development (Latouche, 2004) – argued also by Florian (1983) – emphasizes, therefore the subunitary total efficiency, on the production chain, sometimes significantly reduced.

In the last century there was discovered another analytical paradox, related to scarcity of resources, supported by intellectual arrogance. Some scientists believe that technological solutions and other new resources appear "automatically" (and /or expand linear inside of economic processes) contemporary with the exponential use of existing ones. The number of critical (endangered) resources, which can be found in existing

⁵ The choice in traditional societies is usually "out" of this limited framework (known as selfishness).

resources, has increased also in recent decades (NRC of NA, 2008; Giampietro & Mayumi, 2009). This is also an argument of joint management of resources in order to decrease overall consumption through production related to economic optimum. The economic optimum can be worked out similar with an economic best level for large communities. It shows that the general costs (infrastructure, environment protection, research activities) are increasing, so if they are added together, they can become smaller by dividing the volume of resources used at production size. Their size can decrease by reducing request/offer oscillations in the economic system and through finding alternative solutions and through unified effort.

The framework of evolution-development of European economy, established by various strategies, is analyzed by partial sequences, explained by these analytical findings, but from different perspectives, without ensuring uniform measurement of total effects and efforts of the EU economy. Some of the first analysis, made more than half a century ago, acknowledge the need to convergent development or at least, of such need (Scitovsky, 1958). Without being an explicit recognition, the principle of regional convergence was assumed since the establishment of the European Union. Recently the analysis are being rerun, but social analysis becomes predominant to the economic one (Rosamond, 2000) and the correct measurement (but not exact, Georgescu-Roegen, 1971) tends to be avoided. The attempt of accurate measurement of concrete matter-energy forms appears necessary, especially in the context of wide economic oscillations, such as the recent crisis.

The measurement of regional development has not, in a strong way, the analytical basis. The lack of explanation (and operationalization) of regional convergence in terms of generalized exchange advantage, has the similar consequences as the concept of sustainable development. Both concepts provide a general framework that can become badly "placed" in the absence of adequate explanations or its operationalization. Similarly, the lack of some correlated development, location-relocation, the foreign investment analysis in the context of local development –, the study of globalization limits for example, for limiting it from rising of the trade costs –, may distort in the next period the validity of this EU's strategic objective. The Manoilescu scheme has simple, analytical and operational algorithms and relatively easy to follow.

Some prestigious researchers talk about – thus tacitly assume that – the lack of comparative advantage validity, in its original form, in measuring of economic development. The comparative advantage is the most operational application of the principle of minimum effort (Dogaru, 2006). The comparative advantage requirements provides "at sight" the ways that, respecting the requirements of minimum effort to choose between two (3, 4, ..., n) products, it can win bilateral (multilateral) through cooperation.

In addition, in its original form, not embellished analytical, comparative advantage explains the discrete choice, always valid in exchange acts, suitable to an anthropomorphic way of thinking. Manoilescu explained in detail a remarkable property of comparative advantage, that has not yet been surveyed, its extension at community level. Manoilescu has not explained, strictly theoretically, by demonstrating measurement formulas, the intuitive-rational the weakness of choosing by an individual from n of 2 products in the process of elimination variant.⁶ The intuitive perception of mutual advantage in its extreme form, the gain more than the partner one (von Mises, 1949), reveals us the selfish nature (at desire level) of the human being.

⁶ The demonstration is similar to rule of "9 elimination" from mathematics, keeping the best variant. Using the fixed base index of prices of two countries can find a measure of this choice. See some simple applications of the purchasing power parities (Dogaru, 2003; Kravis et al., 1975).

3. THE STAGES OF ANALYTICAL EFFICIENCY MEASUREMENT OF MATTER-ENERGY EXCHANGES

Analytical understanding of this analytical framework allows us to observe the European model of development. It is based, in our view, on two key initial goals: social welfare (Atkinson, 2002) and joint management of resources – partially explained both by researchers in a sufficient manner – but, as shown through separate analysis, missing the whole analysis. It was fulfilled by Manoilescu through generalized scheme of Ricardo comparative advantage.⁷ Currently, after the substantiation of basic algorithms on arithmomorphic stage and after studying the article from 1940, it can be developed using all discoveries of Manoilescu. The scheme still has some limitations, which should be taken into account, especially in dialectic stage).

Separate identification of similar requirements does not provide a sufficient condition to model of the economic process (elementary /aggregate one) as a whole. In the current research of goods choice in European model, the results synthesis of the two scientists are important, because they have studied the economic processes, starting to the need to save resources and cooperation, through joint management of resources.

These issues have become evident as necessary after several decades of their formulation. Thus it can be said that they anticipated the development of the next economic processes – Georgescu-Roegen by using the argument of joint management of resources and Manoilescu by supporting European convergence. Although social welfare missed in the last centuries (see Buchanan, in Atkinson, 2002), the current trend is to increase the income to the EU-27 by the existence of regional convergence objective.

The European economy pattern has synthesized, after a half century, three main objectives, in which, the regional convergence is essential. The use increase of labor force and the cross-border cooperation can be considered complementary as significance. The current European strategy based on these objectives, explains the need for convergence, achieved through formal measures, nominal-value type, by adding externally. The lack of analytical algorithms, placed in a logical order in the aggregated elementary processes of EU –, thus regarding large regions or country one in terms of material-energy use – is an obvious fact for the projection of the European economy.

The projection lack of regional specialization and of measurement by benefits at the most detailed level possible in terms of comparative advantage, for product groups, local communities, supports in a weak way the consistency of the European economy. The projections can be made on successive periods using analytical verified tools from the Economics of the last two centuries (Manoilescu, 1940; BLS of DOL, 1997). Acceptance of globalization without studying the effects can lead evolution to directions, different from the projected ones for the EU New Member Countries.⁸

The benefits of explicit (projected) choice of (new) manufactured products at regional level, by measuring comparative advantage to each participating region (country), may have disappeared at the third best. This measurement according to efficiency generated through cooperation can be accepted by the majority of participants in economic processes, producers and consumers.

In real economies it can be considered that the first best is, in our opinion, minimizing of loss, related to efficiency with subunitary ratio accepted in thermodynamics, partially compensated through qualitative leap of new recipes (products) and of internally added processes. The second best is due to oscillation, and finally, generating the loss of resources due to significant mismatch of supply and of demand. Excessive fluctuations in supply and demand are unnecessary wastes of the two basic resources, natural resources and labor force. From these resources is issued the loss of real economic value and, in the same time, the nominal value is constantly increasing. This fundamental contradiction marks nominal competitive economies that use money as a real commodity

⁷ The name of Manoilescu generalized scheme was proposed by (Dogaru, 2000).

⁸ Krugman & Venables (1995) refer to exacerbation of potencies of globalization.

(warehouse for goods exchange). The third best refers to optimize the exchange between large collectivities using the Manoilescu scheme and taking into account the correction of errors recently identified of this scheme. There are losses resulting from these oscillations (significant), similar to the way in which from the economic processes can result the waste, which also uses other resources (Georgescu-Roegen, 1971) Projective form of human activity on an individual level and in parallel, qualitative aggregate for human collectivities, can tends to minimize (partial) loss, based on minimum effort. This effort requires saving human energy, with priority of material energetic resources, generally measured related to convergence objective by the welfare indicator, through increasing individual incomes.

The European simile of using energy and matter may be designed in four phases:

1. Inventory of the main resources available and accessible to be jointly managed in coming decades, with an overall estimate of the level of the century. A more detailed analysis of smaller periods will be made, emphasizing the present period. This analysis will be estimated for every two years. The matter-energy consumption will estimate in parallel at regional level the production of the main locations (regions) of the European economy. The goods and resulting wastes will be stored and transported between these locations. It will estimate the resources used in various forms of matter-energy. It will examine the relations between matter and energy in technological assessment and economic analysis. It will apply the Georgescu-Roegen (1979)'s solution.
2. The employment projection, following a similar DRI model (BLS of DOL, 1997). Estimating labor force for long periods, with details for the close periods, ensures consistency over coordination indicators, such as: active population-total population, real unemployed population (regardless of statistical definition of unemployment)-active population, pensioner population-working population, young population / in learning- total population.
3. The exchanges will be projected, according to the calculation of comparative advantage using the Manoilescu scheme, including the framework and information from the two previous stages. It will be estimated the production of objects, energy, which will be achieved per regions, according to the estimated level of consumption. The production will fluctuate in the current competitive economy, but will have lower margins. The estimates will be made public with the basic features of standard products in order to optimization the rational consumption of private or community use, to reduce (self-) manipulation in choice process.
4. The operational focusing (predominantly) on research of (new) products, based on lower resource consumption throughout the entire cycle. The issues will be finalized by obtaining objects (products, technologies, methods of organization), so to obtain real increasing comparative advantage. The subordination order of using of research results in making decision is the following: (a) projection results about resources – strategies on the next century and linking with other areas (Japan, USA, China, India, Russia etc.); (b) the economic results to identify resources restrictions, of limitations on human behavior, technological trends in terms of economy (efficiency); (c) the scientific and technological achievements to be reached in the next period. These three directions will be unified within the making-decision process.

The exploratory replay will be done permanently by the links which are important because they allow the whole operation, of aggregate process of the European economy. The details further of the choice step are done according to (Manoilescu, 1940).

Some requirements and features can be identified in the choice process. The multiple choice comes down to binary choosing (two by two products) until remain two products. The fixing solution of the reference product (after the homogenization of products through hedonic analysis) to compare a group of products allows us to eliminate

analytical gaps. Manoilescu (1940) has fixed an intuitive continuum of choice process that will need to be examined.

The choice of goods producing in one or more regions will take into account such characteristics as the population volume, available resources, specialization of the profession and, primarily, the need for convergence – increasing GDP /value added. Hence the need for appropriate use of comparative advantage Ricardo generalized, and therefore, joint use of resources. The final step is to choose the solution of the new added value, increasing for all the regions (large collectivities) of EU-27. New value added is an economic "invention" of the last century, being supported in analytical plan by the concept of nominal monetary surplus.

In such "oscillating" excessive conditions of market the increment may be distorted the use of existing resources. Georgescu-Roegen and Manoilescu not found a solution because is maintaining the vitiation of the currency instrument. The discovery of a trade surplus has been boosted by the shift from real facts: specialization, because of population growth and of process in line, being completed to the domination by the currency, which established further the final domination of nominal surplus.

According to the requirements of simile, the products can be manufactured in various regions, at the required volume of consumption, taking account the production optimum, trade costs and added value. If the added value is identical at (all) product (s) then the solution given Ricardo is valid in very few cases (Manoilescu, 1940). Otherwise, in the majority of cases, of three degree phenomena, the Manoilescu solution is valid for regional economies, including the European ones.

The similar compared products are not homogeneous and the arithmomorphic solution is limited using the hedonic comparison (regression, etc.) on the main features of the product (matter solution). Every form of energy requires some technology involving the use of various resources so that in this case can do analysis and evaluation separately for every forms of energy (energy solution). But the energy have no a location without the existence of matter. Consequently, the choice of goods containing energy has the operational meaning, so that the Manoilescu-Georgescu-Roegen solution is based.

4. CONCLUSIONS AND FINDINGS

The proposed simile uses the Roegenian method with two-phases, arithmomorphic and dialectic phases, continue and complement each other (Dogaru, 2008, also in Giampietro and Mayumi, 2009). For the arithmomorphic phase is need the correct measurement of choice of energy forms according to the total EU (Whole) energy saving and an objective – increasing GDP per capita, simultaneously in all EU regions. Within the dialectic stage is made the shift analysis through economic processes for decreasing the intermediate consumption, by eliminating the consumption of luxury products and services, as unnecessary.

The proposed simile underlines a step towards the correct measurement (not necessarily accurate) and, partly, towards dialectic explanation. The calculation of for large collectivities (regions), can be used in any situation. The idea of denying a general principle can not be accepted and is subordinated to the minimum effort, either in original form, to Ricardo, either in the Manoilescu form (Dogaru, 2006a) The comparative advantage is explained and/or measured by numerous scientists, including the founders of economic science. The comparative advantage has an analytical limit, due to, mainly, the tools proposed for measurement by human beings. Its limits are derived mainly either from the comparison of qualities through hedonic method using synthetic measurement of stochastic feature or from limiting the analysis to a number of products and /or local communities (Dogaru, 2006b). The analysis EU-27 may be rebutted by an analysis of the global economy and a number of product analysis; similarly, by the same lack of analysis at the level of the roegenian Whole.

Developing of the proposed simile into model, even a sum of subroutines from future model of European economy, can be done relatively easily, together with more accurate

tests for measuring the intensity of EU relations, by example, using the results of the EU for continuing EU KLEMS 2003 project in this direction. Specialization, even with the possibility of multiplying of production in two/many locations, but to maintain optimum of efficiency of production is a basic requirement. Increasing the value added per capita, given the increasing value / person is sufficient. The simile provides support to minimize fluctuations in the use of energetic-material resources. It also supports the elimination relative loss of resources related to the myth of nominal growth of economic value, within process of development (as growth). This phenomenon explains partially Jevons paradox (Polimeni et al., 2008) in a competitive and strongly oscillating economy.

REFERENCES

- Atkinson, T. 2002. "Reassessing the Fundamentals: Social Inclusion and the European Union", *Journal of Common Market Studies* volume 40, number 4, 2002.
- Bureau of Census. 2002. *Statistical Abstract of US 2001*, Bureau of Census of US, Washington.
- Bureau of Labor Statistics of Department of Labor (BLS of DOL). 1997. *Handbook of Methods*, Washington, BLS of Department of Labor, April 1997.
- Dogaru, V. 2000. "The theoretic scheme of the international trade. The generalizing of the Manoilescu's formula", *Romanian Statistic Magazine*, pp. 45-64, July 2000.
- Dogaru V. 2003. *The Population Income and the Prices of Food Products. Comparative analyse of countries trend between 1950-2002*, Expert Publishing House, Bucharest.
- Dogaru, V. 2006a. *Manoilescu generalized scheme regarding the international goods exchange – a general presentation*, Economic Issues (Probleme economice), no. 226-227, The National Economic Research Institute, Romanian Academy.
- Dogaru, V. 2006b. *The comparative advantage principle – between general validity and his demythification*, Economic Issues (Probleme economice), no. 229-230, The National Economic Research Institute, Romanian Academy.
- Dogaru, V. 2008. "Roegenian Method and Comprehension of the Economic Processes", in *Proceedings of the 5th International Seminar on Quality Management in Higher Education, June 2008*, Performantica Publishing House, Iasi.
- Dogaru, V. 2010. "Modeling regional convergence in the European Union – some limitations of Manoilescu solution", in *Proceedings of WSEAS Conferences "Economy and Transformation Management"*, Timisoara, 24-26 October 2010 (forthcoming).
- Dulcan D. C., 2008. *Looking for the lost meaning (In cautarea sensului pierdut)*, Eikon Publishing House, Cluj-Napoca.
- Eatwell, John, Milgate, Murray and Newman, Peter ed. 1987. *The New Palgrave: A Dictionary of Economics*, Macmillan and Stockton, London and New York.
- Florian, M. 1983. *Recessivity as word structure (Recesivitatea ca structura a lumii)*, (tome I, 1983, tome II, 1987), Eminescu Publishing House, București
- Giampietro, Mario and Mayumi, Kozo. 2009. *The Biofuel Delusion: The Fallacy of Large Scale Agro-Biofuel Production*, Earthscan, London.
- Georgescu-Roegen, Nicholas. 1971. *The Entropy Law and the Economic Process*, Harvard University Press.
- Georgescu-Roegen, Nicholas. 1979. "Energy Analysis and Economic Valuation", *Southern Economic Journal*, Vol. 45, No. 4 (Apr., 1979), pp. 1023-1058.
- Kravis Irving B, Kenessey, Zoltan, Heston, Alan, Summers, Robert (KKHS). 1975. *A System of International Comparisons of Gross Product and Purchasing Power*, Baltimore, The John Hopkins University Press..
- Krugman, P. & Venables, A. J. 1995. "Globalization and the Inequality of Nations" *The Quarterly Journal of Economics*, vol. 110(4), pp. 857-80, November.
<http://ideas.repec.org/a/tpr/qjecon/v110y1995i4p857-80.html>
- Latouche, Serge. 2004. *Survivre au developpement*, Editions Mille et une nuits, Paris.
- Maddison, Angus. 2001. *The World Economy: A Millennial Perspective*, Paris, OECD.
- Manoilescu, M. 1929/1937. *Die nationalen Produktivkrafte und der Aussenhandel. Theorie des internationalen Warenaustausches*, Junker und Dünhaupt, Verlag, Berlin, 1937 (other translations: *Theorie du protectionnisme et de l'echange in national*, Bibliotheque Internationale d'economie politique, 382 p. M. Giard, Paris, 1929; *The Theory of Protection and International Trade XXXI + 226 p.*, P. S. King & Son, London, 1931).

- Manoilescu, M. 1934. *Le siècle du corporatisme – Doctrine du corporatisme intégral et pur*, Alcan, Paris.
- Manoilescu, M. 1938. *Essays in the Philosophy of Economics*, Monitorul Oficial, Bucharest.
- Manoilescu, M. 1940. Die theoretische Problematik des Außenhandels. Synthese – Beweisführung – Polemik, *Weltwirtschaftliches Archiv (Review of World Economics)*, 51/1, January 1940.
- National Research Council of the National Academies (NRC of NA). 2008. *Mineral, Critical Minerals and The U.S. Economy*, The National Academy Press US.
- Polimeni, John M., Mayumi, Kozo, Giampietro Mario and Alcott, Blake. 2008. *The Jevons Paradox and the Myth of Resources Efficiency Improvement*, Earthscan, London.
- Rosamond, B. 2000. *Theory of European Integration*, Palgrave, New York.
- Scitovsky, T. 1958. *Economic Theory and Western European Integration*, Stanford University Press, Stanford.
- Szenberg, M., editor. 1992. *Eminent Economists. Their Life Philosophies*, Cambridge University Press.
- United State Department of Labour (USDL). 1999. *Multifactor Productivity Trends, 1997*. Washington, Department of Labour. <http://stats.bls.gov/mprhome.htm>
- von Mises, Ludwig. 1949. *Human Action. A Treatise on Economics*, Yale University Press, New Haven.

SESSION 1.4

ENERGY METABOLISM AND THE ENVIRONMENT

Bardi U., Lavacchi A., and Yaxley L.

EROEI AND NET ENERGY IN THE EXPLOITATION OF NATURAL RESOURCES. A STUDY BASED ON THE LOTKA-VOLTERRA MODEL

Cherubini F., Peters G. P., Berntsen T., Strømman A. H., Hertwich E.

BIOENERGY AND ITS ACTUAL MITIGATION OF CLIMATE CHANGE: DOES CARBON NEUTRAL MEAN CLIMATE NEUTRAL?

Martínez A., Uche J., Carrasquer B., Rubio C.

SEARCHING MEANINGFUL INDICATORS WITHIN THE WATER WORLD. HOW CAN EXERGY HELP?

Bukowski M., Manteuffel Szoega H.

ENVIRONMENTAL IMPACT OF USING DIFFERENT ENERGY SOURCES FOR FAMILY HOUSE HEATING

EROEI AND NET ENERGY IN THE EXPLOITATION OF NATURAL RESOURCES. A STUDY BASED ON THE LOTKA-VOLTERRA MODEL

Ugo Bardi^{1*}, Alessandro Lavacchi², and Leigh Yaxley³

¹ *Dipartimento di Chimica - Università di Firenze*

Via della Lastruccia 3, Sesto Fiorentino [Fi] – Italy

² *ICCOM-CNR, Polo scientifico di Sesto Fiorentino – 50019 Firenze - Italy*

³ *Society for Petroleum Engineers, 10777 Westheimer Rd., Suite 1075, Houston*

ABSTRACT

Recently, it has been shown that the Lotka-Volterra model can be used for a quantitative description of the exploitation of non renewable resources in a free market economy [Bardi and Lavacchi 2009]. The present paper examines how the model describes the behavior of the system in terms of energy return for energy invested (EROEI) and Net Energy (energy returned minus energy expended). We show that these factors are correctly described by the model and that the evolution of the system leads to conditions in which an energy resource – such as crude oil – can be extracted in condition of negative net energy and EROEI smaller than 1.

Keywords: Hubbert, energy, overexploitation, crude oil, whale oil, resource depletion, lotka-volterra, EROI, EROEI

1. INTRODUCTION

The “Hubbert Model” [Hubbert 1962] is an empirical model developed in the 1960s to describe the production of crude oil or – in general – of mineral resources. It is often observed that when a mineral resource is exploited in free market conditions, the extraction – or production – curve is bell shaped; nearly symmetric and with a maximum that is often termed “Hubbert peak” [Bardi and Pagani 2008]. It is generally believed that the Hubbert behaviour is related to the declining Energy return for energy invested (EROEI or EROI) of exploitation [Hall et al. 2008, Murphy 2009]. That is, the decline in production is the result of the increasing costs of extraction. With lower profits, companies involved in extraction find themselves short of capital and must reduce investments. This process leads, eventually, to “peaking” of production and to its successive decline. This behaviour can also be observed for renewable resources which are exploited so fast that there is no time for the system to replenish the available stock. In this case, the term often used is “overexploitation” [Catton 1982] and has been observed, for instance, in the case of whale oil in 19th century [Bardi 2007]

In the present paper we will examine how a simple model can quantify the factors that lead to peaking and overexploitation. The model used here is based on the well known Lotka-Volterra (LV) model [Lotka 1925, Volterra 1926], also known as the “predator-prey” and “foxes and rabbits” model. Real biological systems are too complex to be captured by a simple two species model, but the LV model has found applications in economics, where it is sometimes known as “Free Access” model [Smith 1968]. In a recent study, Bardi and Lavacchi [2009] found that it is possible to use a simplified version

* Corresponding author; E-mail: ugo.bardi@unifi.it

of the model – one that doesn't account for the reproduction of the prey – to describe a number of cases of exploitation of non-renewable resources, such as crude oil, or of slowly renewable ones, such as whale oil. According to this study, this simplified LV model is equivalent to the Hubbert model. We will show how the LV model can provide a quantification of factors such as the EROEI and the Net Energy of the exploitation process and confirm that the Hubbert behavior is related to a declining energy yield.

2. EROEI AND NET ENERGY

Exploiting an energy resource can never been 100% efficient. For instance, if we consider oil wells, in order to exploit the chemical energy stored in the well, we must expend some energy in operations such as prospecting, drilling, extracting, processing, transporting etc. EROEI (Energy Return for Energy Invested) is defined as the ratio of the energy obtained from the resource to the energy expended in all production phases, including also the energy involved in the disposal of the equipment and installations involved [Hall et al. 2008, 2009]. A related concept is that of Net Energy, defined as the energy produced minus the energy expended in the whole process of exploitation. When the EROEI is equal to 1 or lower, the net energy is zero or lower. There exist also other concepts related to the energy efficiency of a process (e.g. “transformity”) which will not be considered here.

EROEI is a very useful concept for understanding the real value of a resource in economic and energy terms. Obviously, larger EROEIs are preferable and an EROEI smaller than one corresponds to a net loss of energy. However, some processes may be carried out even at low EROEIs, even smaller than one, as a result of specific choices of the economic system. As an example, biofuels, and in particular ethanol, have a low EROEI [Pimentel and Patzek, 2005] but are produced using energy subsidies from higher EROEI fossil fuels.

Despite its usefulness, the definition of EROEI suffers of some uncertainty for two reasons: one is that energy quality is not taken explicitly into account, the second is that the boundaries of the system can be defined in different ways. For the first problem, energy quality, a better definition of EROEI would be in terms of exergy, that is the fraction of energy involved which able to do useful work, rather than simply energy. In practice, this is rarely a serious problem. The other uncertainty in the EROEI calculation, the boundaries of the system, is more complex. What factors should be exactly taken into account in defining the energy expended? For instance if the technicians involved in oil extraction take a plane to reach an oil field, the energy involved in the trip should obviously be accounted as a cost. But, if the same technicians take a vacation to Hawai'i, should the fuel energy of the trip be taken into account? It is customary to consider only some of these costs, but not others, according to norms defined in the “Life Cycle Analysis” (LCA) concept. These norms are defined in protocols such as, for instance, the ASTM E1991 – 05. If, however, one wants to take into account everything that is done with energy source (including, e.g. people's vacations) then we may speak of “full EROEI” or “societal EROEI.” [Hall et al. 2008, 2009]. The value of societal EROEI determines the surplus that can be utilized for all those activities that are considered part of what we call “civilization”, from cathedrals to poetry. The LCA-EROEI of specific processes will be normally larger than societal EROEI, because the latter includes more energy consuming processes.

3. THE LOTKA-VOLTERRA MODEL APPLIED TO RESOURCE EXPLOITATION

Lotka [1925] and Volterra [1926] developed a well known model of “predator-prey” relationship in simple biological systems. The model was shown to be usable in economy, and in particular in the case of fisheries [Smith 1968]. In the implementation of the model developed for the exploitation of mineral resources [Bardi and Lavacchi, 2009] it was assumed that there are two main stock variables involved in the model: resources and

capital. The amount of available resource is defined as the “resource stock,” R . The other main variable of the model is the aggregate amount of economic resources being utilized in the exploitation; that is equipment, land, knowledge, human work, and similar. We called this aggregate amount “capital stock,” C . R' and C' are defined as the flow (the variation as a function of time) of, respectively, resources and capital. Further parameters of the model are the initial stocks of resource (R_0) and of capital (C_0).

The resource (the “prey”) can be extracted in proportion to the available capital (the “predator”) and, at the same time, in proportion to the amount of the resource stock. This assumption is intuitively justified; the more equipment [e.g. oil rigs] is available, the higher the amount of resource that can be extracted/produced. On the other hand, there must be something to extract and the model assumes that the extraction rate will be proportional to the amount available. Implicitly, this assumption involves that resources are “graded” and that the “easy” (less expensive) resources are extracted [or produced] first.

The other fundamental assumption of the model is that capital is generated in an amount proportional to the amount of extracted resources. In other words, the resource stock is partly transformed into capital stock; let's say that the extracted oil is used to provide the energy necessary to build more oil rigs and other facilities. In more general terms, this transformation is generated via the sale of the resource on the market and the profits are used to create the equipment and facilities to produce more resource. Finally, we also assume that capital is dissipated over time.

These assumptions can be stated in mathematical form as two coupled differential equations derived from the Lotka-Volterra model. One term of the standard LV model is missing, that of the reproduction of the prey, that here is assumed not to occur or to occur very slowly.

1. $R' = -k_1CR$
2. $C' = k_2CR - k_3C$

This simplified model can describe a number of historical cases of resource exploitation, when the resource is non renewable (e.g. crude oil) or slowly renewable (e.g. whale oil) [Bardi and Lavacchi 2009].

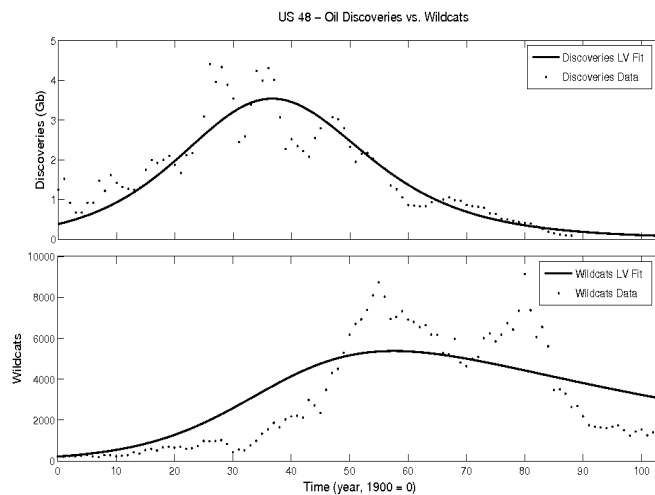


Figure 1. Fitting of the data for oil discovery in the US 48 lower states and of the number of wildcats. In this case, the number of wildcats is proportional to the capital used by the oil industry in the effort of discovering the resource (oil wells). From [Bardi and Lavacchi 2009]

In order for the model to be applicable, it is necessary to have data on at least some of the main parameters in the equations; e.g. historical data on production and on aggregate capital accumulation. These data may be measured in terms of “proxies”; e.g. using the tonnage of the whaling fleet as a proxy for the total capital available to the whaling industry. An example of the results obtained for the US-48 lower states historical

data on crude oil production is shown in the figure 1. Here, the “discoveries” parameter is used as a proxy for resource production and the number of wildcats as a proxy for the

aggregate capital used by the oil industry for prospecting in the area considered. Other cases for which the model was found to give a good or acceptable production were gold production in South Africa and in California, whale oil production in 19th century and crude oil production in Norway [Bardi and Lavacchi 2009].

4. EROEI AND NET ENERGY IN THE LOTKA-VOLTERRA MODEL

This Lotka-Volterra model – just as any model attempting to describe a physical system - must satisfy the laws of physics and, in particular, those of thermodynamics. It is clear that even in its simplest implementation, that of two biological species (foxes and rabbits), the two stocks involved are energy stocks. What the model describes is the flow of energy from one stock (rabbits) to another (foxes). The internal energy of the model is given by the sum of the stock of the resources and of capital. In the case of a non renewable resource, this total stock cannot increase, otherwise we would have creation of energy from nothing. There exist values of the constants of the model that provide such a creation and these values are forbidden by thermodynamics. In particular, if the stocks are measured using the same units, k_2 must be smaller than k_1 otherwise the transformation of rabbits into foxes would occur with an energy gain. If $k_1=k_2$, the transformation occurs at no metabolic cost: rabbits are not eaten, but hypnotized and convinced to be foxes.

Parameters such as EROEI and Net Energy are not explicitly expressed in the equations of the LV model, but can be calculated from the available parameters which, as mentioned before, include energy and energy flow. In a previous study [Bardi and Lavacchi 2009], we defined the “yield” of extraction as (R/C) , that is the ratio of production to capital. However, the relation of this parameter to the concept of EROEI needs to be discussed more in detail.

If we apply the LV model to an actual economic process, we are interested in defining parameters that measure its efficiency. In general, we are interested in maximizing production and minimizing costs and, in this case, we are interested in maximizing production and capital accumulation. The “costs” in the model are defined as the only term that produces an outflow (dissipation) of the accumulated capital. Therefore, we can define the economic yield of the process as the ratio of production (k_1RC) or capital accumulation (k_2RC) to capital dissipation (k_3C). The ratio of production to dissipation appears to be the factor most closely related to EROEI.

An example will clarify these considerations. Let's consider the common application of the LV model to a hypothetical two-species systems of foxes and rabbits (in this case, sterile rabbits). “Production” is the flow of captured rabbits (k_1RC). Capital accumulation is the number of newborn foxes (k_2RC). Capital dissipation can be seen as the energy spent by foxes in hunting rabbits. This parameter will be proportional to C (number of foxes) and will actually be k_3C if foxes do nothing else in their life except hunting for rabbits and related activities. We need also to assume that foxes die of starvation but not by old age. This may be an approximately good view of the behavior of foxes and other animals.

Given these assumptions, the EROEI of the foxes/rabbits system can be defined as the ratio of the produced energy in terms of captured rabbits, k_1RC , to the expended energy for hunting (k_3C). If – as mentioned before - it is assumed that foxes do nothing in their life except reproducing and hunting rabbits then we arrive to the formula:

$$\text{EROEI} = k_1R/k_3$$

However, in an economic process such as oil extraction only a fraction of the profits from oil extraction will be re-invested in the same process. For instance, only part of the profits made by the oil industry will be re-invested in prospecting for oil and for developing oil fields and related facilities. We may consider that the definition given before, $\text{EROEI} =$

k_1R/k_3 , actually measures the “full EROEI” or “societal EROEI”, and not just the extraction related EROEI. It will be therefore smaller than the conventional “LCA-EROEI”. In any case, the concept that EROEI is proportional to R (the resource stock) remains useful in the reasonable assumption that the fraction of profits re-invested by the industry in the exploitation of a resource remains approximately constant over the resource lifetime.

Note that there is no element in the formula that would stop processing when the EROEI becomes smaller than one; when that occurs, exploitation will continue utilizing previously accumulated energy resources. Note also that, since production is given by R' , a maximum in the production curve will correspond to a flex in the EROEI curve.

From this result, we can proceed with the determination of the form for Net Energy (NE) which we may define as production minus dissipation. That is

$$NE = C(k_1R - k_3)$$

We see that for R sufficiently small, that is in the final stages of exploitation, the net energy of the system becomes negative and it remains so. We can also write this relation as:

$$NE = CR(k_1 - k_3/R)$$

Assuming that R is relatively large, that is we are not at the final stages of the exploitation process, we can approximate NE as equal to k_1CR , that is to production. Therefore, we expect Net Energy to have a maximum that takes place, approximately, near the production peak.

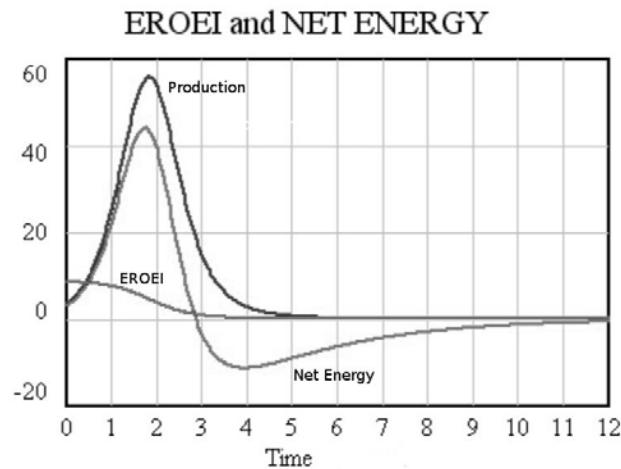


Figure 2. Qualitative solutions of the LV-system obtained using the Vensim software. The parameters reported are production, net energy and EROEI.

Qualitative simulations performed using the Vensim software confirm both this statement and the one that EROEI should have a flex in correspondence to the production peak; as shown here:

These calculations qualitatively correlate with the historical data on the EROEI of oil extraction from the US-48 lower states (Murphy 2009, Cleveland 2005) as shown in the following figure. Despite the small number of points available, it is possible that the flex in the EROEI curve occurs around 1970 and therefore it corresponds to the production peak in the region.

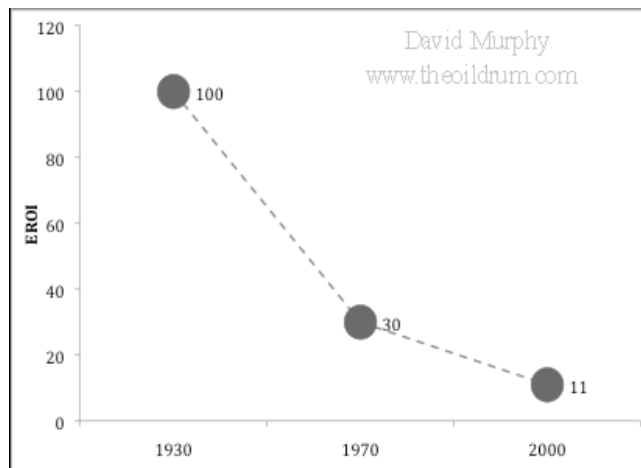


Figure 3. Historical EROEI of crude oil extraction in the lower 48 US states. Figure from [Murphy 2009]

These considerations raise the question of whether it is possible to use the Lotka-Volterra model to determine the EROEI instead of using the standard LCA analysis. There are two problems in this sense: the first is the use of proxy data for the fitting of the historical trends, the second is that EROEI, as defined within the model, implies that all the energy produced by the system is reused to produce more energy, an obviously non realistic assumption. Regarding the use of proxy data, it is possible to normalize the LV equations and to obtain the real EROEI as a function of the measured parameters. For the second problem, however, the LV model cannot say anything about the societal decision of which fraction of the profits from the exploitation of a resource have to be allocated to further exploitation. Indeed, tests made with the US-48 crude oil system studied in a previous paper [Bardi and Lavacchi 2009] show that the EROEI calculated from the LV model is much smaller than the LCA calculated EROEI [Cleveland 2005], as expected. On the basis of the available data, the “LV-EROEI” for crude oil in the US lower 48 states is calculated as around 4 at the start of the production cycle, whereas the LCA data indicate a value of about 100. This result may indicate that only about 5% of the energy produced by oil extraction was re-invested in oil extraction.

The results presented here have to be considered as preliminary and tentative, but we can conclude that the LV model offers useful insights on the mechanism of resource exploitation and it may offer in the future a route for modeling and understanding economic processes which are vital for society. More than its capability of quantification, the LV model offers a simple mental tool – a “mind sized model” [Papert 1980] to grasp the main elements of the overexploitation of natural resources (including the ability of the atmosphere to contain CO₂ without overheating) which is the main problem that our civilization is facing today.

REFERENCES

- Bardi U. 2007 “Energy Prices and Resource Depletion: Lessons from the Case of Whaling in the Nineteenth Century” *Energy Sources, Part B: Economics, Planning, and Policy*, Volume 2, Issue 3, pages 297 - 304
- Bardi U., and Pagani M., 2008, “Peak Minerals”, *The Oil Drum*, <http://www.theoildrum.com/node/3086>
- Bardi, U. and Lavacchi A., 2009, “A Simple interpretation of Hubbert's model of resource depletion” *Energies* 2(3), 646-661; doi:10.3390/en20300646
- Catton William, R. 1982 *Overshoot*, University of Illinois press. ISBN 0-252-009826
- Cleveland, C. J., 2005, “Net energy from the extraction of oil and gas in the United States”, *Energy* Volume 30, Issue 5, Pages 769-782

- Hall, C.A.S.; Powers, R.; Schoenberg, W. 2008 "Peak Oil, EROI, Investments and the Economy in an Uncertain Future". In *Renewable Energy Systems: Environmental and Energetic Issues*. Pimentel, D., Ed.; Elsevier: London, 2008; pp. 113-136
- Hall, Charles, Stephen Balogh, Stephen, and Murphy David J. R., 2009 "What is the Minimum EROI that a Sustainable Society Must Have? *Energies* 2009, 2, 25-47; doi:10.3390/en20100025
- Hubbert M.K. 1962, "Energy Resources. A Report to the Committee on Natural Resources:National Accademy of Sciences",*Nat. Res. Council* publ. 1000-D Washington DC, p. 54.
- Lotka, A. J. 1925 *Elements of physical biology*. Baltimore: Williams & Wilkins Co. 1925
- Pimentel D. and Patzek T. W. 2005 "Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower" *Natural Resources Research* Volume 14, Number 1, 65-76, DOI: 10.1007/s11053-005-4679-8
- Murphy, David, 2009, "The Net Hubbert Curve: what does it mean?" *The Oil Drum* <http://netenergy.theoildrum.com/node/5500>
- Papert, Seymour 1980, *Mindstorms*, New York, U.S.A
- Smith, V. L., 1968 "Economics of Production from Natural Resources" *The American Economic Review*, Vol. 58, No. 3, Part 1, pp. 409-431,
- Volterra, V., 1926 "Variazioni e fluttuazioni del numero d'individui in specie animali conviventi" *Mem. R. Accad. Naz. dei Lincei. Ser. VI*, vol. 2. 1926.

BIOENERGY AND ITS ACTUAL MITIGATION OF CLIMATE CHANGE: DOES CARBON NEUTRAL MEAN CLIMATE NEUTRAL?

*Francesco Cherubini^{*1}, Glen P. Peters², Terje Berntsen², Anders H. Strømman¹,
Edgar Hertwich¹*

¹ *Department of Energy and Process Engineering, Norwegian University of
Science and Technology (NTNU), NO-7491 Trondheim, Norway*

² *Center for International Climate and Environmental Research – Oslo (CICERO),
Oslo, Norway*

ABSTRACT

Bioenergy systems are carbon neutral because the CO₂ released from biomass combustion approximately equals the amount of CO₂ sequestered by biomass re-growth. Starting from this, biogenic CO₂ emissions are not considered as a greenhouse gas (GHG) which contributes to climate change, and the bioenergy system is automatically assumed to be climate neutral. This means that biogenic CO₂ emissions are de facto ignored in Life Cycle Assessment (LCA). This widely used default assumption underestimate the importance of the time perspective: before it can be captured by forest re-growth, this CO₂ emission remains in the atmosphere for a certain number of years and it actively contributes to climate change. The challenge is to measure this contribution with unit based indicators to be included in LCA. The inherent difficulties to quantify this effect have so far hindered any possible estimation.

The calculation methodology proposed here is based on an atmospheric flow approach: the decay of biogenic CO₂ is modelled as an impulse response function originated from the perturbation caused by this emission to the climate system. The absolute global warming potential of biogenic CO₂ is estimated and the resulting value is related to that one of anthropogenic CO₂ emissions. This leads to an index (GWP_{bio}) that is similar to the equivalency factors elaborated for the various GHGs. Since this index is expressed in function of the rotation period of the biomass, the outcomes of these calculation procedures can be applied to all the different biomass species, from annual row crops to tropical, temperate and boreal forest.

The influence on LCA results of the inclusion of the climatic effect of biogenic CO₂ emissions is shown with an application to a case study. This case study deals with a biorefinery system producing transportation biofuels, biochemicals and bioenergy from forest wood (Norwegian Spruce, boreal forest). When the GWP_{bio} index is included in the assessment, the GHG savings of the biorefinery are drastically reduced and its contribution to climate change becomes approximately similar to that of the respective fossil reference system.

Keywords: Global Warming Potential, bioenergy, climate change, LCA

1. INTRODUCTION AND BACKGROUND

The United Nations Framework Convention for Climate Change (UNFCCC) with the help of the Intergovernmental Panel on Climate Change (IPCC) developed the rules for compiling national GHG inventories and the guidelines for national reports of GHG emissions under the Kyoto protocol (UNFCCC, 2003). CO₂ emissions reporting under this accounting framework are compiled in different ways depending on whether the carbon has a biological or fossil origin. National reporting of fossil CO₂ emissions is based on an atmospheric flow perspective, since the CO₂ flux to the atmosphere is assigned to the country where combustion (or oxidation, in general) takes place and not to the country of origin of the raw material. Contrarily, IPCC recognizes that CO₂ emissions from biomass combustion can be counted using two alternative methods, either as emissions from land use or energy emissions (IPCC, 2006). To avoid double counting, the IPCC assigns

* Corresponding author; E-mail: francesco.cherubini@ntnu.no; Phone: +4773598942

biogenic CO₂ emissions to the land use sector and not to the energy sector. Therefore, net carbon stock changes in biomass carbon pools due to bioenergy are reported within the Land Use Land Use Change and Forestry (LULUCF) sector of the biomass supplier country. In this case, a stock change approach is used. This is an indirect measure of the contribution to climate change, since it is assumed that carbon accumulated in the terrestrial pools is not in the atmosphere, and then stock changes reflects the impact on the atmosphere. This convention is used since it is generally easier to estimate carbon stock change than atmospheric flux (Cowie and Schlamadinger, 2006). This biogenic CO₂ neutrality principle is even followed by most of the GHG balances of bioenergy systems available in the scientific literature, which generally find a reduction in the contribution to climate change when compared to fossil reference systems, provided that changes in terrestrial carbon pools are minimized (Petersen Raymer, 2006; Quirin et al., 2004; Searcy and Flynn, 2008). Obviously, the main reason for this result is the absence in GHG balances of CO₂ emitted from biomass combustion (Rabl et al., 2007).

Following these guidelines, direct CO₂ emissions from biomass combustion for bioenergy can be considered climate neutral and are not counted in GHG inventories. However, as it has been already acknowledged in the past, this universally adopted assumption neglects the fact that *“all CO₂ is equal in the atmosphere”* (Möllersten and Grönkvist, 2007). Möllersten and Grönkvist state that the IPCC only provides vague guidance concerning this crucial matter, and further detailed analysis would be highly desirable in order to clearly account for biogenic CO₂ emissions. It is somewhat surprising that a proper method to deal with this topic have not been presented before in the literature. The objective of this paper is then to provide a first insight in this open issue, starting from the consideration that whatever CO₂ emission directly affects the carbon cycle (and hence the climate) of the planet: from a mere atmospheric perspective, there is no difference whether this CO₂ comes from biogenic or fossil sources.

2. GWP AS METRIC FOR CLIMATE CHANGE

The effects on climate change of CO₂ emissions need to be measured with a proper metric. Despite some well known shortcomings of GWP, the use of this metric brings some important advantages: the IPCC has set precedence for using it, it is adopted by the Kyoto Protocol and is by far the most common index in existing primary research studies. These aspects make the introduction of GWP for biogenic CO₂ emissions in current scientific community easier than other metrics.

The GWP index heavily relies on the concept of radiative forcing. This is the perturbation of the earth energy balance by a climate change mechanism; its evaluation over a proper time horizon represents the cumulative radiative forcing, which is often referred to as Absolute Global Warming Potential (AGWP). In mathematical terms, this is given by the integral over time of the product between the radiative efficiency of the gas (α) and the decay function, $y(t)$, that defines its lifetime in the atmosphere per a pulse emission (C_0):

$$AGWP = C_0 \int_0^{TH} \alpha \cdot y(t) dt \quad (0.1)$$

where TH is the time horizon representing the upper limit of the integral. The radiative efficiency (α) of CO₂ is (Forster et al., 2007):

$$\alpha_{CO_2} = 5.35 \ln \left(\frac{[CO_2]}{[CO_2^*]} \right) \quad (0.2)$$

Where $[CO_2]$ is the concentration in the atmosphere after small perturbation and $[CO_2^*]$ is the initial concentration of CO₂ in the atmosphere. If the background

concentration of 378 ppm provided by the IPCC report is used, and a perturbation of 1 ppm is applied, the value of the radiative efficiency for CO₂ is $1.41 \times 10^{-5} \text{ W m}^{-2} \text{ ppb}^{-1}$.

The decay functions are different for each GHG (see Figure 1). Contrarily to the other most important GHGs (CH₄ and N₂O) where the lifetime corresponds to the single e-folding time, the decay of a CO₂ pulse emission approaches an asymptotic value which is different from zero. This has important implications on the estimation of the respective AGWP: the integral of this decay curve from zero to infinity is equal to infinity, and therefore the respective AGWP cannot be analytically determined. In 1996, the IPCC adopted the CO₂ decay function by Joos et al. (1996), with finite time horizons (after 20, 100 and 500 years) for the integration (Schimel et al., 1996). As specified by the IPCC itself, these different time horizons have been selected to quantify AGWP of CO₂ in a uniform way and they should not be considered as having any special scientific significance. GWPs were then elaborated for all the different GHGs (denoted as *i*) according to this equation:

$$GWP_i = \frac{AGWP_i}{AGWP_{CO_2}} = \frac{C_0 \int_0^{TH} \alpha_i \cdot y_i(t) dt}{C_0 \int_0^{TH} \alpha_{CO_2} \cdot y_{CO_2} dt} \quad (0.3)$$

In this way, GWP acts as a metric able to aggregate emission of the various gases to a common unit (kg CO₂-eq./unit). In Table 1, GWPs for given time horizons are shown for the three most important GHGs, together with their lifetime and radiative efficiency.

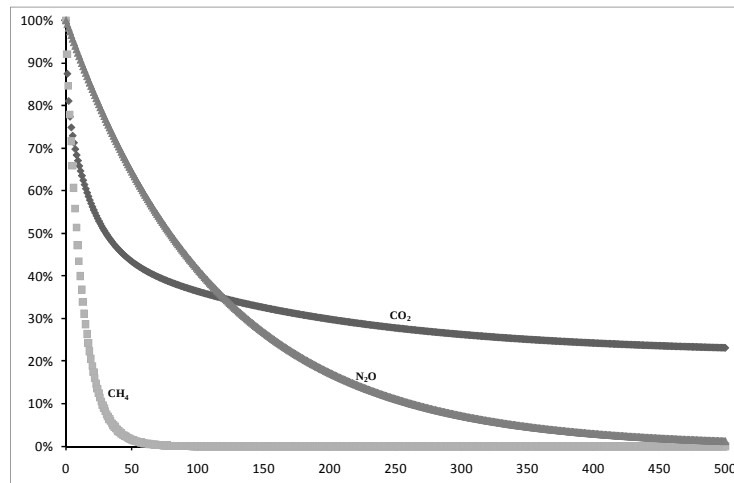


Figure 1. Atmospheric decay of the three most important GHGs.

Table 1. Lifetime, radiative efficiency, and GWPs for different time horizons of the three most important GHGs.

GHG	Lifetime	Radiative efficiency	GWP	GWP	GWP
	(years)		20 years	100 years	500 years
		(W m ⁻² ppb ⁻¹)			
Carbon dioxide (CO ₂)	n.a.	1.4×10^{-5}	1	1	1
Methane (CH ₄)	12	3.7×10^{-4}	72	25	7.6
Nitrous oxide (N ₂ O)	114	3.03×10^{-3}	289	298	153

3. ATMOSPHERIC DECAY OF ANTHROPOGENIC CO₂

Anthropogenic CO₂ emissions cause a perturbation of the Earth climate system and their decay from the atmosphere can be modeled as an impulse response function (IRF)

(Joos and Bruno, 1996; Tubiello and Oppenheimer, 1995). The theoretical justification for the use of IRFs is that the dynamics of a linear system can be fully characterized. In the case of CO₂, several functions elaborated through a suitable fitting procedure have been proposed (Joos et al., 1996; Joos et al., 2001; Lashof and Ahuja, 1990; Maier-Reimer and Hasselmann, 1987). These functions were obtained as a response to the ocean-atmosphere/biosphere carbon climate models. In all the cases, carbon dioxide does not follow a simple decay according to one single lifetime, but its decay is described by several time constants and there is a fraction of the initial pulse emission that always remains in the atmosphere (Figure 1). The decay function used by IPCC is that obtained from an updated version of the Bern Carbon Climate (CC) model (Joos et al., 2001). This is a cost efficient carbon cycle-climate model which includes chemistry, radiative forcing, climate and carbon cycle modules to simulate the evolution of CO₂ and other radiative agents and climate. A detailed description of this model can be found elsewhere (Joos et al., 1996; Joos et al., 2001).

The value of this function at any time represents the fraction of the initial emission which is still found in the atmosphere, and the removed fraction corresponds to the ocean/biosphere uptake. The function has the following analytical form:

$$y_{CO_2}(t) = A_0 + \sum_{i=1}^{i=3} A_i e^{\left(-\frac{t}{\tau_i}\right)} \quad (0.4)$$

Equation 0.4 is used in equation 0.3 to determine the AGWP of anthropogenic CO₂ emissions, which is used as reference to estimate the GWPs of the different GHGs. The atmospheric decay of anthropogenic CO₂ is given by a superposition of a number of exponentials of different amplitude A_i and relaxation time τ_i . The values of these factors are reported in Table 2. The amplitude A_0 represents the asymptotic airborne fraction of CO₂ which remains in the atmosphere because of the equilibrium response of the ocean-atmosphere system. The amplitudes A_i may be interpreted as the relative capacity of the other sinks, which are filled up by the atmospheric input at rates characterized by the relaxation time scales τ_i . This means that these time scales determine the redistribution of anthropogenic CO₂ emissions in the climate system and are linked to the time scales of the natural carbon cycle. According to this decay trend, more than 50% of the initial input has been removed from the atmosphere within two decades after emissions through uptake by the upper ocean and the fast overturning reservoirs of the land biosphere. However, around 30% of the pulse emission is still in the air after 100 years, and 22% after one thousand years; this fraction is only very slowly reduced further by ocean-sediment interaction and the weathering cycle (Archer et al., 1998).

4. CLIMATIC EFFECT OF CO₂ EMISSIONS FROM BIOMASS

The version of the Bern CC model adopted by IPCC does not include formulations for forest management nor bioenergy production. Maybe, the reason can be that forestry for wood production is expected to have a small net effect on the overall C budget, since harvest tends to be compensated by re-growth (Houghton, 2003). Therefore, the Bern 2.5model is line with the IPCC guidelines on the neutrality of biogenic CO₂ emissions if biomass is replanted. This concept overlooks the importance of the time perspective: in order to be neutral, this system needs time, from 1 year (e.g. agricultural crops) up to 100 years (e.g. forest wood), depending on the particular biomass species and climate. During this period, CO₂ molecules stay in the atmosphere and the overall Earth climate system is perturbed. In this section we propose a method which can be used to estimate the contribution to climate change of biogenic CO₂ emissions.

This method is based on the following modeling assumptions:

1. The calculation procedure developed in this paper are applied to a well-defined schematic case study which is suitable to show the approach proposed (see Figure 2);
2. all biomass is burnt in one step;
3. the resulting CO₂ emission is modeled as a pulse;
4. the biomass harvested comes from an even-aged vegetation stand (representing the starting condition) which is clear cut;
5. the land is immediately re-vegetated with the same biomass species after harvesting
6. the re-growth of the biomass captures the same amount of CO₂ that was released by combustion;
7. only one rotation is assumed;
8. CO₂ emissions from loss of carbon pools other than above ground vegetation, like soil and litter, are not considered here.

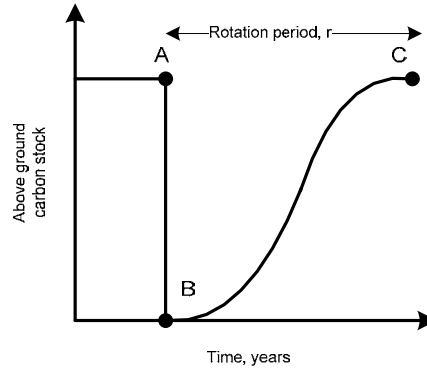


Figure 2. Simplified scheme of the case modeled in this paper. A: biomass stand at steady state; B: all above ground carbon is harvested and emitted to the atmosphere as CO₂. Simultaneously, the same biomass is replanted and starts growing by sequestering the CO₂ released from combustion; C: the same quantity of carbon originally released is sequestered once again in the vegetation at the end of the rotation.

According to the most common practice in growth modeling in forestry (Rossi et al., 2009; Swallow et al., 1990), the rate of biomass growth (or re-growth, in our case) can be modeled as a normal distribution (Gaussian), expressed as atmospheric carbon uptake in vegetation in function of the rotation period of the biomass. This is a probability density function that has the following analytical form:

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \quad (0.5)$$

where the parameters μ and σ are the mean and the variance. It is here assumed that the mean occurs in correspondence of the year with the maximum carbon uptake by the vegetation re-growth, assumed to be at half of the rotation period ($\mu = r/2$). The variance determines the width of the normal distribution, and it is assumed to be equal to half mean ($\sigma = \mu/2$).

The integral of this function leads to the cumulative density function, which is the total carbon accumulated in the biomass stand along the full rotation. This integral can only be expressed in terms of the error function *erf*:

$$G(t) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{t-\mu}{\sigma\sqrt{2}} \right) \right], \quad \operatorname{erf}(t) = \frac{2}{\sqrt{\pi}} \int_0^t e^{-x^2} dx \quad (0.6)$$

These functions are used to model the removal of the biogenic CO₂ emissions from the air and can be adapted to specific biomass species or climate and soil conditions.

4.1 Impulse Response Function (IRF) for biogenic CO₂

An IRF for CO₂ released from biomass combustion is derived through the combination of the IRF for anthropogenic CO₂ with a function modeling the removal of CO₂ from the atmosphere through vegetation re-growth. In mathematical terms, the development of the atmospheric CO₂ concentration can be approximated by the convolution integral of the emission with the atmospheric pulse response function, following a conventional and widely used approach (Siegenthaler and Oeschger, 1978). Following this approach, the atmospheric CO₂ concentration $f(t)$ after a pulse emission can be represented as the sum of earlier emissions g at times t' multiplied by the fraction still remaining in the atmosphere after time $t - t'$:

$$f(t) = C_0 \cdot y(t) - C_0 \cdot \int_0^t g(t') \cdot y(t-t') dt' \quad (0.7)$$

where C_0 is the pulse emission of CO₂ to the atmosphere, $y(t)$ is the exponential decay of the CO₂ airborne fraction (as derived from the Bern CC model) and $g(t')$ is the rate of biomass re-growth (i.e. the normal distribution of equation 0.5), which is here modeled as a negative emission removing the CO₂ originally released. Thank to this convolution it is possible to link CO₂ emissions and atmospheric CO₂ levels, provided that the changes remain in the linear range of the buffer factor.

Then, equation 0.7 can be explicitly written as follows:

$$f(t) = C_0 \cdot \left(A_0 + \sum_{i=1}^3 A_i e^{-\frac{t}{\tau_i}} \right) - \int_{t_0}^t C_0 \cdot \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t'-\frac{r}{4})^2}{2\left(\frac{r}{4}\right)^2}} \cdot \left(A_0 + \sum_{i=1}^3 A_i e^{-\frac{t-t'}{\tau_i}} \right) dt' \quad (0.8)$$

Unfortunately, this integral cannot be solved analytically, and exact results can be obtained by numerical approximation only. Equation 0.8 is then integrated between zero and the time horizon to estimate the respective AGWP, which is used to determine the GWP_{bio} index.

5. RESULTS

Figure 3 shows the atmospheric decay of biogenic CO₂ as obtained from the calculation procedure previously described. The IRF approach gives a curve that is more complex and less intuitive than that for anthropogenic CO₂, since the curve has some negative values. At first sight, this may appear as a contradiction, because the amount of CO₂ in the atmosphere is lower than the level before the emission, but there is a technical reason for that. As already mentioned, CO₂ is taken up in different biogeochemical reservoirs at different time constants, as mathematically represented by equation 0.4; as implicitly assumed by equation 0.7, the same time constants are applied even to CO₂ uptake in vegetation. This means that soon after the emission, when the biomass growth rate is still slow, a significant fraction of the CO₂ originally released is stored in the slowly reacting reservoirs. Then, when most of the CO₂ is taken up by the vegetation sink, the carbon stored in these reservoirs will be released to the atmosphere at a very low rate, so that, in the long term, the airborne fraction of biogenic CO₂ approaches zero.

In Table 2, the GWP_{bio} index is reported in function of the rotation period of the biomass. These results are elaborated for 2 time horizons (100 and 500 years). In GHG

accounting, this index must be multiplied by the biogenic CO₂ emissions from biomass combustion to get the respective climatic effect in terms of g CO₂-eq./unit. The procedure is identical to that adopted for GHG emissions occurring along the life-cycle bioenergy chain, which are multiplied by the specific GWP equivalency factors.

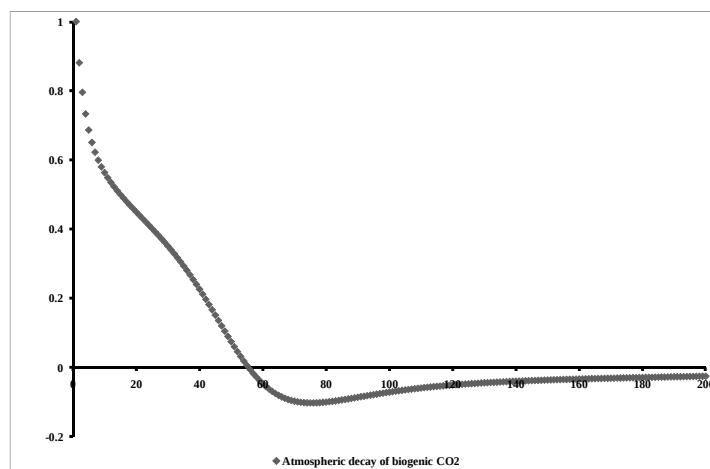


Figure 3. Decay trend of biogenic CO₂ from the air following the approach elaborated in this paper ($r = 100$).

Table 2. GWP_{Bio} index calculated for 2 different time horizons, 100 and 500 years.

Rotation r	IRF GWP _{bio} TH = 100	GWP _{bio} TH = 500
1	0.004	0.002
2	0.01	0.003
8	0.03	0.01
10	0.04	0.01
20	0.08	0.02
30	0.12	0.02
40	0.16	0.03
50	0.21	0.04
60	0.25	0.05
70	0.30	0.05
80	0.34	0.06
90	0.39	0.07
100	0.43	0.08

6. APPLICATION TO BIOREFINERY

The approach based on the IRF for the contribution to climate change of biogenic CO₂ emissions is here applied to a biorefinery system producing multiple products (bioethanol, power, heat and chemicals) from forest wood, harvested in central Norway. Further details on this biorefinery system, which is compared with a fossil reference system producing the same amount of products and services, can be found in (Cherubini et al., 2010). The total GHG emissions from the biorefinery system are equal to 87 kt CO₂-eq./a (average case), about 25% of those released from the fossil reference system (corresponding to 344 kt CO₂-eq./a). When the GWP_{bio} index of 43% (boreal forest, rotation period assumed of 100 years, 100 years time horizon) is included in the calculation, the GHG emissions of the biorefinery system increase up to 366 kt CO₂-eq./a, slightly larger than those of the reference system (see Figure 4). This means that if the climatic effect of biogenic CO₂ emissions is taken into account the biorefinery system does not contribute to mitigate climate change.

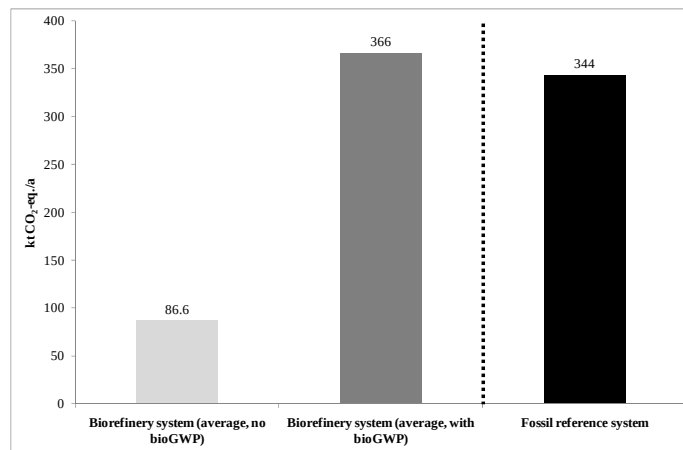


Figure 4. GHG emissions of the biorefinery system with and without the GWP_{bio} index in comparison with the fossil reference system.

7. DISCUSSION AND CONCLUSION

The consideration of an index to measure the contribution to climate change of biogenic CO₂ emissions has important consequences in GHG accounting methods and implications for climate policy strategies. When this index is included in GHG balances, the GHG emissions of the bioenergy system may considerably rise, especially if long rotation biomass species are used as raw materials. This hinders the suitability of existing forest biomass to reach the near term climate policy targets. Besides the decreases in terrestrial carbon pools due to biomass production for bioenergy which are still to be considered and reported in the LULUCF sector, this index make even the last step of the bioenergy chain, the biofuel combustion step, responsible of a CO₂ emission. Then, both the supplier country and the consumer country are burdened by a contribution to climate change. It is even of noteworthy importance the role played by the GWP_{bio} in the ongoing discussion on the GHG accounting frameworks which are warmly debated in the scientific community: the Stock Change Approach (SCA) and the Atmospheric Flow Approach (AFA) (Pingoud et al., 2010; Searchinger et al., 2010).

Implications at a national and policy level are also relevant. At a national level, the responsibility schemes between countries change, since the exporting country is still responsible for possible changes in terrestrial carbon pools and the importing country, where biofuels are burnt, becomes responsible for a contribution to climate change due to biogenic CO₂ emissions. At a policy decision level, new strategies which take into account the climatic effects of the temporary carbon loss needs to be established in order to reach the near term climate policy targets.

This work even acts as starting point for future research activities and investigation of specific case studies in this field. The theoretical basis and calculations here developed can be used to model more specific case studies, with customized biomass growth curves, multiple rotations, particular management strategies, different starting conditions (e.g. afforestation rather than deforestation) or other specific factors. These outcomes can be even integrated within software tools modeling the effects of biomass production on terrestrial carbon pools and the climate and software for GHG balances of bioenergy systems.

REFERENCES

Archer D., Kheshgi H., Maier-Reimer E. (1998) "Dynamics of fossil fuel neutralization by Marine CaCO₃". *Global Biogeochemical Cycles* 12:259-276.

- Cherubini F., Michelsen O., Strømman A.H. (2010) "LCA of biorefinery systems: environmental impacts, biogenic C flows, allocation issues and biodiversity implications of a Norwegian Wood-based concept", *18th European Biomass Conference and Exhibition, Lyon, France*. pp. 2030-2034.
- Cowie A., Schlamadinger B. (2006) "Stock changes or fluxes? Resolving terminological confusion in the debate on land-use change and forestry". *Climate Policy* 6:161-179.
- Forster P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, Dorland R.V. (2007) "Changes in Atmospheric Constituents and in Radiative Forcing", in: e. a. S. Solomon (Ed.), *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge, UK.
- Houghton R.A. (2003) "Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000". *Tellus* 55B:378-390.
- IPCC. (2006) "Guidelines for national greenhouse gas inventories", Volume 4 - *Agriculture, forestry and other land use*, Intergovernmental Panel on Climate Change.
- Joos F., Bruno M. (1996) "Pulse response functions are cost-efficient tools to model the link between carbon emissions, atmospheric CO₂ and global warming". *Physics and Chemistry of The Earth* 21:471-476.
- Joos F., Bruno M., Fink R., Stocker T.F., Siegenthaler U., Le Quéré C., Sarmiento J.L. (1996) "An Efficient and Accurate Representation of Complex Oceanic and Biospheric Models of Anthropogenic Carbon Uptake". *Tellus* 48B:397-417.
- Joos F., Prentice I.C., Sitch S., Meyer R., Hooss G., Plattner G.-K., Gerber S., Hasselmann K. (2001) "Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios". *Global Biogeochemical Cycles* 15:891-907.
- Lashof D.A., Ahuja D.R. (1990) "Relative Contributions of Greenhouse Gas Emissions to Global Warming". *Nature* 344:529-531.
- Maier-Reimer E., Hasselmann K. (1987) "Transport and Storage of CO₂ in the Ocean – an Inorganic Ocean-circulation Carbon Cycle Model". *Climate Dynamics* 2:63-90.
- Möllersten K., Grönkvist S. (2007) "All CO₂ is equal in the atmosphere--A comment on CDM GHG accounting standards for methane recovery and oxidation projects". *Energy Policy* 35:3675-3680.
- Petersen Raymer A.K. (2006) "A comparison of avoided greenhouse gas emissions when using different kinds of wood energy". *Biomass and Bioenergy* 30:605-617.
- Pingoud K., Cowie A., Bird N., Gustavsson L., Ruter S., Sathre R., Soimakallio S., Turk A., Woess-Gallasch S. (2010) "Bioenergy: Counting on Incentives". *Science* 327:1199-b-1200.
- Quirin M., Gartner S.O., Pehnt M., Reinhardt G.A. (2004) "CO₂ Mitigation Through Biofuels in the Transport Sector: Status and Perspectives", in: I. f. E. a. E. R. (IFEU) (Ed.), Main Report, Heidelberg, Germany. pp. 57.
- Rabl A., Benoist A., Dron D., Peuportier B., Spadaro J.V., Zoughaib A. (2007) "How to account for CO₂ emissions from biomass in an LCA". *International Journal of Life Cycle Assessment* 12:281.
- Rossi S., Tremblay M.-J., Morin H., Savard G. (2009) "Growth and productivity of black spruce in even- and uneven-aged stands at the limit of the closed boreal forest". *Forest Ecology and Management* 258:2153-2161.
- Schimel D., Alves D., Enting I.G., Heimann M., Joos F., al. e. (1996) "CO₂ and the carbon cycle", in: J. T. Houghton (Ed.), *IPCC Second Scientific Assessment of Climate Change*, New York, U.S.
- Searchinger T.D., Hamburg S.P., Melillo J., Chameides W., Havlik P., Kammen D.M., Likens G.E., Obersteiner M., Oppenheimer M., Robertson G.P., Schlesinger W.H., Lubowski R., Tilman G.D. (2010) "Bioenergy: Counting on Incentives--Response". *Science* 327:1200-a-1201. DOI: 10.1126/science.327.5970.1200-a.
- Searcy E., Flynn P.C. (2008) "Processing of Straw/Corn Stover: Comparison of Life Cycle Emissions". *International Journal of Green Energy* 5:423 - 437.
- Siegenthaler U., Oeschger H. (1978) Predicting future atmospheric carbon dioxide levels. *Science* 199:388-395.
- Swallow S.K., Parks P.J., Wear D.N. (1990) "Policy-relevant nonconvexities in the production of multiple forest benefits". *Journal of Environmental Economics and Management* 19:264-280.

Tubiello F.N., Oppenheimer M. (1995) "Impulse-response functions and anthropogenic CO₂".
Geophysical Research Letters 22:413-416.

UNFCCC. (2003) *Estimating, reporting, and accounting of harvested wood products*, Technical
paper FCCC/TP2003/7.

SEARCHING MEANINGFUL INDICATORS WITHIN THE WATER WORLD. HOW CAN EXERGY HELP?

Amaya Martínez^{*1}, Javier Uche¹, Beatriz Carrasquer¹, Carlos Rubio²

¹ CIRCE Intitute- University of Zaragoza, Spain

² Faculty of Mechanical Engineering, UMSNH, Morelia, Mich., México

ABSTRACT

Social, environmental and physical indicators are becoming fundamental in our society. From their demand by policy makers as summaries of the changing reality to their deep analysis to assure their completeness, they are part of our days. Water world is not an exception and more and more ratios and parameters are being introduced in the field as a way to synthesize varied information.

In this sense, indicators are called to play a relevant role in the water bodies characterization, as well as in the specification of river basin management plans designed as fulfillment of different international water- related legislations and general requirements. Those regulations and guidelines, however, are generally quite ambiguous and they claim about *appropriate indicators*, without much additional precision.

In addition to the information provided by the currently used indicators such as water footprint, water stress, virtual water, water use per capita, water consumption in the different economic sectors, fresh water depletion rates or the water demand and supply, for instance, additional and physically-based indices are demanded from a sustainable perspective.

Within this context, Exergy and, in particular, the exergy costs, are proposed in this paper as a comprehensive tool to assess the environmental water cost in particular and to study water issues in general. The exergy analysis of water comprises the quantity and the quality of the water flow and, in addition to that, it evolves in the space, as well as in the time.

The particular characteristics of exergy as working tool to define water indicators are explained in this work. It is shown that exergy can be a part of the searched meaningful set of indicators and indices for water resources studies searched by the World Water Assessment Program, the European Water Directive and some other international organism.

Specifically, the *exergy cost* is proposed as a physical indicator to calculate the environmental water cost of water and to compare water supply and water treatment alternatives in a given area. Finally, the different *exergy components* and the *exergy cost* of water within the watershed are calculated for a case study, the Ebro river. Attending to the good ecological state of that basin, this first attempt through the exergy approach lead to an environmental cost of about 1068 M€/year.

Keywords: water indicators, exergy of water, water management

1. INTRODUCTION

The growing interest in the use of indicators and indices is closely connected to the increasing complexity of policy problems and the large amount of available data. Indicators are essentially aimed to simplify, quantify, communicate and order through the relation and integration of collected information. They allow then the comparison of different issues, initially disconnected.

Attending to their definition, to indicate is to give evidence or to be a signal or a symptom. Although different meanings can be found in bibliography regarding the indicator concept, the core idea is that it has to enable to characterize a system or situation, to compare and to draw conclusions after establishing a common ground.

Indicators can be an instrument to communicate policy objectives and results to the public because they are able to reflect and inform about a complex idea. They are

* Corresponding author; E-mail: amayamg@unizar.es

everywhere as a part of our everyday lives. They are used to observe, describe, and evaluate actual states, to formulate desired states or to compare an actual with a desired state. These simple numbers, descriptive or normative statements can condense the enormous complexity of the world around us into a manageable amount of meaningful information.

Water world is not an exception and more and more ratios and parameters are being introduced in the field as a way to synthesize varied information. The development of good indicators is nevertheless challenging (WHO, 1999).

1.1 Water management and water info

The guidance philosophies for the management of water supplies varied during the last twentieth Century. Until 1950, water management was governed by the goal of moving water to where it was most needed, particularly for irrigation of agricultural lands. The belief that pollutants would disperse in the water, provoked that rivers and lakes were used to carry away wastes from municipal and industrial uses. At present, the focus of water management has shifted to considerations of municipal, agricultural, and industrial supplies, water quality, and the protection of aquatic ecosystems.

Therefore, water is becoming a very valuable good: water as a resource is nowadays comparable to oil; it is essential to all daily human activities. Water has very rarely been the main ingredient in international conflicts, but it is often factored into the problem due to its economic importance (Gleick, 2008). Consequently, it is a crucial issue to adequately organize the water information.

In this sense, within the water sector, indicators have been commonly used from the beginning of the reported figures. They provide varied and rich information, from the simple descriptive figures (available fresh water, water withdrawal, water consumption...) to predictive situations which can be calculated when time series based models are linked to indicators. At the same time, the regular measurement of those parameters provides time series, which show trends that may provide information on the system's functioning or its response to management.

Effectively, the description of the state of the resource is the most common use of indicators, namely available water resources, water demand or water supply with reference to a specific location and context. But indicators are a fundamental tool in the assessment function of water resources as well. An indicator value can be compared to a reference condition that represents some desired state. The specification of a reference condition depends strongly on the purpose of the indicator, its users, and the issue being reflected. Thus, reference conditions include policy targets, sustainability criteria and historical states.

That idea is, in fact, the background of the European Water Framework Directive, came into force in 2000, which set the ecosystem preservation in the core of the water policy issues. It is aimed to achieve the good ecological status of the water bodies through the corresponding actuations on the hydrological units, named as *Programmes of Measures*. The objective state of water bodies in order to fulfill with the Directive's requirements is defined through chemical, physical, biological and hydro-morphological indicators.

They have to be measured along the time. However, the mentioned legal text just indicates in its 4th Article the necessity of including the adoption of the *appropriate indicators*. Not much additional details are provided, only general guidelines. In consequence, its implementation is still quite open to water managers' interpretation.

At this point and, in addition to the social and commonly used physical and chemical indicators, the Second Law of Thermodynamics and, in particular, the exergy property, could be called to play a significant role in the task required by the European legislation.

In the study presented in this work, the energy needed to restore the quantity and quality in the rivers is a key issue. In this sense, energy efficiency in the proposed water utilities and the minimization of energy resources consumption are crucial.

As mentioned, the final objective of the Directive is to provide each river basin with a water plan including all water resource management elements necessary for achieving the indicated objectives. Water planning is a way to improve and provide support to the appropriate management, facilitating decision-making processes. Furthermore, it can be understood as an iterative process, in the sense that it must be flexible in order to incorporate new criteria and adapt itself to changing circumstances.

1.2 Water variables, indicators and indexes

First of all, it could be useful to define the concepts of *variable*, *indicator* and *index* because they commonly appear in related text and they are sometimes mixed. As a summary, it can be said that a *variable* is an observed datum from basic statistics or monitoring. An *indicator*, however, can be understood as a second step when those collected data are aggregated through mathematical and scientist procedures, describing the system or process, and providing significance beyond the simple value of its components. As an example, the amount of rainfall and runoff are variables, as well as evaporation and transpiration rates. Then, when these two latter are aggregated, the indicator on evapotranspiration is obtained. Further and numerous examples can be found within the water availability and supply framework. Total annual withdrawal, for instance, derives from the addition of surface and groundwater contribution and, at the same time, from the different sites comprising the studied territory. The prevailing criterion behind the specification of an indicator is scientific knowledge and judgment (WWAP-UN, 2003).

Afterwards, such figures can be lumped and then an *index* arises. As examples, the water stress or the aridity index can be named. Water withdrawal and availability are combined to calculate the water stress index; the aridity index of an area can be constructed by aggregating different indicators on water availability and use. To sum up, an index provides synthesized and targeted information for management and policy development. Its sense is not always on scientific justification, but on responding to the societal needs.

2. NATURAL RESOURCES ASSESSMENT AND PHYSICAL LAWS.

Although the fact of using physical laws to assess natural resources is agreed by ecological economist, the way to do it is somehow diverse. At the beginning of the 20th, it was clear that the monetary system was not the adequate way of valuing environment. The idea was elaborated along the decades and, later on, one of the most important and comprehensive contributions to the energy and Thermodynamics history, which linked it with the Economy, was published by Martínez-Alier in 1987 under the title *Ecological Economics: Economics, environment and society* (Martínez-Alier, 1987).

From the Industrial Revolution until today, the development and continuous efficiency improvements of the energetic and industrial sectors have been tightly joined to the Thermodynamics principles. None of the advances can be understood without its proper thermodynamics context. It is worth to highlight that a further step in the valuation of Environment is including the quality and degradation aspects in the analysis. From a physical perspective, it means to include the Second Thermodynamics Law (entropy law). That is, taking exergy as the working tool. Then, First and Second Laws of thermodynamics are useful to determine how much energy is needed at each point in a system, and in what form that energy is acting within the system (Cleveland, 2006).

The resource accounting in terms of exergy has been carried out based on nation or industrial sector scales (Chen, 2006). Dincer (2002) paid much attention to the relationship between energy utilization and the environmental impacts, and highlighted the implication of the exergy analysis to the sustainable development. In addition to its traditional industrial trajectory, the Exergy analysis has been performed in the field of Industrial Ecology to use energy more efficiently (Wall, 1986). In recent decades, utilization of exergy has spread outside of Physics and engineering to the fields of

Industrial Ecology, Ecological Economics, Systems Ecology, and Energetics (e.g., Jørgensen et al., 2000; Rosen and Dincer, 2001; Gong and Wall, 2001; Wall, 2002; Szargut, 2003, 2004).

Focussing the attention in the water bodies, exergy analysis comprises the quantity and the quality of the water flow and, in addition to that, it evolves in the space, as well as in the time: spring water gets degraded as it flows along the river course until the sea. That degradation means a loss in its quantity because of the water uses, as well as a decrease in its quality due to the natural and the anthropic pollution. Numerous contributions can be found in the literature. Hellström (1997, 2003) estimated and compared the exergy consumption of physical resources in some wastewater treatment plants and sewerage systems. Finnveden and Östlund (1997) and Ayres et al. (2002) have developed an Exergy Based Life Cycle Analysis, introducing the concept of exergy into the methodology of environmental life cycle assessment and using it as a uniform indicator of total environmental impact. Chen (2007) developed for a unified objective assessment of water quality, the chemical exergy based evaluation method. While a quantity termed specific standard chemical exergy based on the global reference substances might be adopted, an indicator as specific relative chemical exergy with reference to a spectrum of substances associated with the specified water quality standard is proposed for water quality evaluation. So it has more practical implications, resulting in unified objective quantifiers for the carrying capacity and carrying deficit of water resources. In his study, water qualities of numerous rivers and lakes over the world were evaluated to illustrate the adaptability of the chemical exergy based indicators for water quality evaluation.

In short, the natural degradation of the river occurs when the river swept away different materials in its path; the human one comes from the specific water uses. Those physical interactions are translated into numerical values and the corresponding exergy costs can be calculated and proposed as physical indicators providing valuable information.

2.2 Exergy and cost

According to the review carried out by Torres and Valero (2007), the first proposal in the literature to use the Second Law analysis for costing purposes was made by Keenan in 1932, where he indirectly refers to exergy costing as the means for appropriately apportioning cost associated with the cogeneration of electric power and steam for distribution. Particularly, Keenan pointed out that the value of those products rest in their *availability*, not in their energy. This author, together with Benedict, kept on working on the idea of coupling exergy and cost streams. In the 1960's, Tribus and Evans, made exergy analysis of desalination processes, which led them to the idea of exergy costing and its applications to engineering economics, for which they coined the word *Thermoeconomics*. (Torres and Valero, 2007). The effort of comprehensively apply Thermoeconomics to the analysis, optimization and desing of thermal system was leaded by Gaggioli on the 1980s. From then on, the works regarding to exergy analysis increased. In 1985, Tsatsaronis introduces the key concept of Fuel and Product. Frangopoulos (1983) and Spakovsky (1986) kept working on Evan's proposals.

The General Theory of the Exergy Cost was firstly presented by Valero, Lozano and Muñoz (1986) through a set of three papers published by the American Society of Mechanical Engineers (ASME). They stated the fundamental task of costing as the problem of obtaining the cost of all the physical flows comprising a system, once its limits, as well as its subsystem aggregation level, have been defined. In this sense, they define the exergy cost as the *real amount of exergy required to produce any physical flow in a system whose limits, aggregation level and subsystem efficiencies have been defined*. From then on, many other authors have contributed to the development of exergy and thermoeconomic accounting, completing the existing theories and even opening new research lines. Szargut (1987) gave rise to the *cumulative exergy consumption* concept,

an idea intrinsically similar to the *exergy cost* defined by Valero et al. (1986), i.e., a close to embody energy concept, but using exergy. Later, Gong and Wall (2001) also pointed out that exergy can be defined as a sustainable development registration that emphasizes the connection between generated services or products and used resources. Some authors such as Mora and Oliveira (2006) have more recently used the exergy efficiency as an environmental performance index which includes the aspects of energy efficiency and environmental impact of the energy conversion processes.

Nowadays, the application of the exergy analysis in the evaluation of natural fluxes and resources on Earth (Exergoecology- Valero, 1998) is becoming a useful tool for natural resources accounting. The consumption of natural resources implies destruction of organized systems and dispersion, which is in fact generation of entropy (or exergy destruction). This is why the exergy analysis can perfectly describe the depletion of natural capital and specifically, the degradation of water bodies.

3. METHODOLOGY. PHYSICAL HYDRONOMICS. EXERGY AND EXERGY COST AS MEANFUL INDICATORS

Spanish Water Accounts (Naredo and Gascó, 1994) introduced by first time the Thermodynamics in the water accounting. These authors stated that while the Law of conservation of matter and energy governs water quantity accounts, the Law of entropy governs water quality accounts.

Together with the Entropy Law, the Conservation Law must also be applied to water matter-energy relations: water quantity refers to the quantity of mass or volume, while water quality refers to available energy or exergy it contains, identified with its capacity to react spontaneously. Not intending to deal with the fields of energy involved in the movement of water in the biosphere, this line of research was opened with the calculation of the fields considered to be more relevant and more easily quantifiable in the case of Spain: those related (1) directly with the altitude; the *hydraulic power* (HP) measurable according to mass and height above sea level and (2) inversely with the content of solutes by unit of water mass or volume, or directly with its dilution capacity -*osmotic power* (OP) measurable according to the osmotic pressure exercised by saltwater over the semipermeable piston that puts it in contact with better-quality water-.

Later on, the application of the Exergoecology approach to watersheds has been developed by the authors in the last years under the denomination of Physical Hydromonics. This methodology has been developed as the accounting tool for the WFD application, and it is defined as the specific application of the Thermodynamics to physically characterize the degradation and correction of water bodies. The Second Law of Thermodynamics, through the exergy loss calculation, is the basic working tool in this study. The final objective of PH is to use those calculated physical costs as a guide to calculate and allocate the environmental water costs proposed by the European WFD.

The exergy of a water body is defined by its mass flow and six parameter measurements that characterize the physical conditions of water: temperature, pressure, composition, concentration, velocity and altitude (Zaleta, 1998). The exergy method associates each parameter with its exergy component: thermal, mechanical, chemical, kinetic and potential. Therefore, and starting from these components, it is possible to evaluate in quantitative (flow, Q) and qualitative (specific exergy, b) terms a water body and any water resource characterised by its exergy components (Wall, 1986). Each component should be separately calculated because they have a diverse nature and also because of their quite wide difference in order of magnitude. The sum of all components expresses the exergy of the given water resource and can be understood as the minimum energy required to restore the resource from its Reference Environment (RE).

The physical interactions taking place along the river are translated into numerical values through the PH methodology: it allows expressing the flows involved in the hydrologic cycle in exergy values, that is, into MWh. The exergy of any water flow represents the maximum work that can be obtained from it until reaching the equilibrium

with the reference environment (the ocean) or, it can be also understood as the minimum energy that needs to be invested in order to restore such a resource. Then, the exergy profile of a river can be drawn through the precise identification of the pair quantity and quality at each river stretches. Moreover, that river profile can be obtained for any river state (i.e., the present state, the state of the river in the future, the desired objective state according to the legislation or the natural state of the river).

Valuating the exergy difference between the current state of the river (RS) and the good ecological state (OS) gives an idea about the environmental water cost. That is, the difference between those two river profiles should be overcome in order to reach the objective state of the river.

$$EC = B_{OS} - B_{RS} \quad (1)$$

This idea is, nevertheless, still insufficient because of the inherent irreversibility to any real process. Then, the next step was to introduce the exergy cost (k^*), which informs about the real amount of exergy required to produce any physical flow in a system whose limits, aggregation level and subsystem efficiencies have been defined. Finally, once the real physical cost of the water flow is established, it can be given in economic cost by introducing the energy price in the region when the study is carried out. In this part, both physical direct costs measured in energy units (energy operation cost), as well as physical indirect cost given in monetary units (global investment and maintenance costs), are aggregated.

$$k^* = \frac{F}{P} \quad (2)$$

$$EC^* = k^* \cdot (B_{OS} - B_{RS}) \quad (3)$$

The environmental cost results in energy units (kWh/yr), by application of Eq. (3) and, in addition, it is calculated for each exergy component because the unit exergy cost, k^* , is different for each restoration technology proposed. Then, for instance, waste water treatment plants are proposed to depurate the water flow until the desired quality in the good ecological state and desalination plus pumping plants in those places where water flow is not enough to meet the legal flow requirements. Finally, the environmental cost (EC^*) can be expressed in economic terms by introducing in the analysis the current energy price (about 80 €/MWh).

4. CASE STUDY: EBRO WATERSHED

The Ebro River presents the greatest discharge of any Iberian river. It is the longest in Spain, and the second (after the Tago River) in the peninsula. The north bank of the river is fed first by the rivers of the Cordillera Cantábrica and then by those of the Pyrenees, including the Aragón, Gállego and Cinca-Segre, and to the south generally with a lower discharge, by tributaries from the Sistema Ibérico, including the Oja, Iregua, Jalón and Guadalope. Consequently, the Ebro can be said to drain much of the southern Pyrenees and the northern Sistema Ibérico. Although the climate at its source is Atlantic, the most of the stream flows by a continental climate with low rainfall, hot summers and dry, cold winters.

In spite of the mentioned significant discharge, its flow is irregular along the year (as Mediterranean river) with low levels at the end of summer and high levels during the spring melt of the Pyrenees, leading to a danger of flooding along much of its easterly length (CHE, 2009).

The study of the exergy profiles of the Ebro river provide the information presented in Figure 1 and Figure 2, where the main stream of the river is shown.

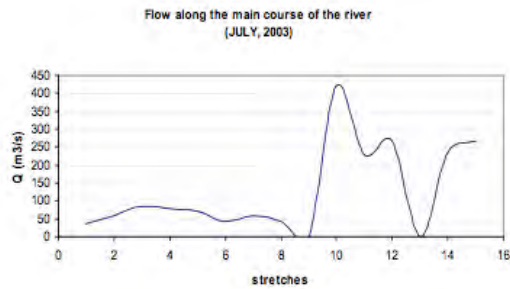


Figure 1. Flow along the main course of the Ebro River in a wet year (July, 2003)

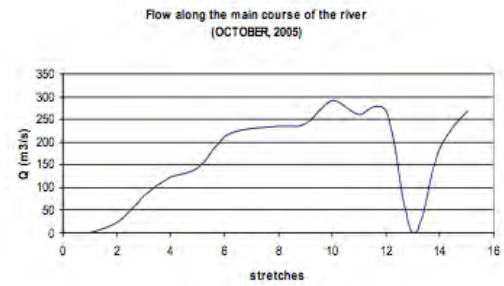


Figure 2. Flow along the main course of the Ebro River in a dry year (October, 2005)

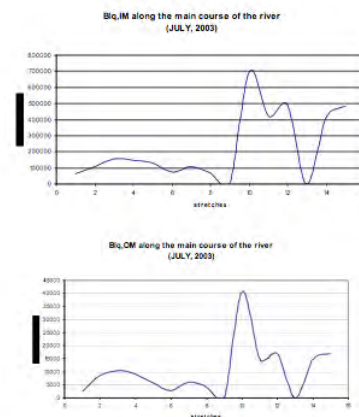
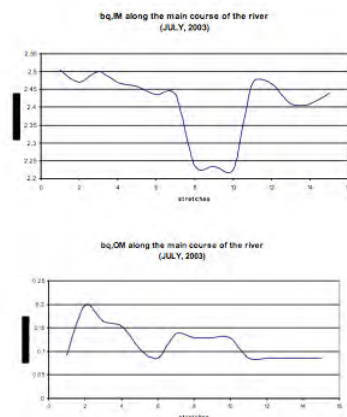


Figure 3. Specific exergy and Exergy along the river course in July for a wet hydrologic year

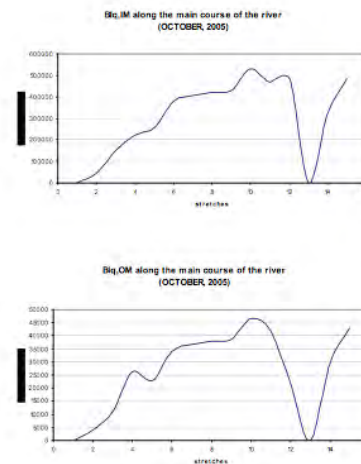
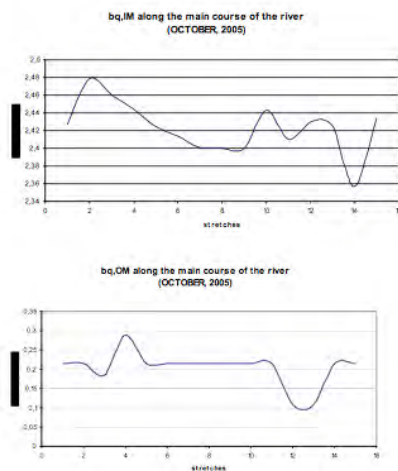


Figure 4. Specific exergy and Exergy along the river course in October for a dry hydrologic year

After carrying out the complete analysis, the EC of water within the Ebro Basin rises up 1,068 M€/yr, what gives a preliminary idea about the effort required to meet the quantity and quality objectives in the water body, according to the WFD. The investment cost for the corresponding facilities needs still to be added; this second part of the study is going to be completed in the following months.

The given EC can be compared to the amount given by the official unit of management of the Ebro River, the Confederación Hidrográfica del Ebro, who indicated that the total cost of the getting the good ecological state could be about 6,000 M€

(Hispagua, 2010), including also biological and hydromorphological issues. Those aspects fall out of scope of PH.

5. CONCLUSIONS

Water-related indicators are becoming more and more relevant in the development of environmental and economical policies. Water is studied from social, environmental and physical perspectives and information. Resulting information has to be provided in an understandable way through variable, indicators and indexes, in order to serve as a mean of communication to policy-makers and the public. Such parameters can evaluate the effect of performed policy actions and plans and also reflect the reality of the system under study along time and space.

For the last decades, efforts are aimed to protect the water ecosystem, preserving or restoring the good ecological state of the water bodies. In particular, the European Water Framework Directive is significantly helping in such effort, since its starting point is defining water as absolutely other than a commercial product but, rather a heritage which must be protected, defended and treated as such. It clearly establishes that waters in the Community are under increasing pressure from the continuous growth in demand for sufficient quantities of good quality water for all purposes. Then, it is aimed to establish a framework for Community action in the field of water policy, looking for the achievement of the good ecological status of the water bodies through the corresponding actuations on the hydrological units, named as programmes of measures. Thus, indicators are called to play a relevant role in the water bodies characterization, as well as in the specification of those river basin management plans.

It has been explained that an indicator can be a simple data point or variable, or can be a simplified value derived using some Mathematics. Probably the most essential criterion for an indicator is that it should enlighten its user and provide a sense of the issue being examined. The most important issue is that the selection of the variable or the mathematical aggregation of several variables gives a clear picture of the issue being assessed, referenced or monitored.

In spite of the goodness of indicators, their importance should not be overestimated. Mind has to be kept open to integrate and combine information coming from different research fields. Any person trained in water management will agree on the huge amount of information associated to the water world. A comprehensive work can not be executed solely by technicians, hydrologists, economists, or any other monothematic specialists. On the contrary, it is possible through the joint efforts of a transdisciplinary team of experts whose approaches managed to overcome, from scientific bases, the difference of specialities involved, and who managed to agree on horizontal problems. Keeping in mind that limitation, the exergy and the exergy costs have been presented in this paper as additional assessment tools.

The final reflexion would be that for every country, no matter its economic position, the environmentally sustainable development and management of water resources has become a critical and complex issue. It is technically challenging and often entails difficult trade-offs among social, economic, and political considerations. Typically, the environment is treated as a marginal issue when it is actually crucial for a sustainable water management. Exergy cost, together with some other biological and hydromorphological indicators, fulfils the opportunity provided by the WFD in relation to water values and resources assessment. Therefore, exergy can be a proper indicator and serve as basis for meaningful indexes such as the exergy cost.

REFERENCES

- Ayres, R.U. and Ayres, L.W., 2002. *A Handbook of industrial ecology*. Edwar Elgar publishing.
Chen, G.Q. 2006. *Scarcity of exergy and ecological evaluation based on embodied exergy*.

Nonlinear

- Science and Numerical Simulation 11, pp. 531-552. Elsevier.
- CHE, 2009. *Datos de la Oficina de Planificación Hidrológica*. Confederación Hidrográfica del Ebro. Ministerio de Medio Ambiente. Available at: <http://www.chebro.es>.
- 9Finnveden, G. and Ostlund, P. 1997. "Exergies of natural resources in life-cycle assessment and other applications". *Energy*. Vol.22 no 9, pp. 923-931. Pergamon.
- Frangopoulos, C.A. (1983). *Thermoeconomic Functional Analysis: A method for the optimal design or improvement of complex thermal systems*. Ph.D. Thesis. Georgia Institute of Technology.
- Gleick, P.H, 2008. *Water Conflict Chronology Pacific Institute for Studies in Development, Environment, and Security*. American University.
- Gong, M. and Wall, G. 2001. "On exergy and sustainable development, Part-2". *Exergy, an International Journal* 4, pp-217-233. Elsevier.
- Hellström, D. 1997. "An exergy analysis for a wastewater treatment plant- an estimation of the consumption of physical resources". *Water Environment Research* Vol. 69, no1. pp. 44-51.
- Hellström, D. 2003. "Exergy analysis of nutrient recovery processes". *Water Science and Technology* Vol.48 no1 pp. 27-36. IWA Publishing.
- Jørgensen, S.E. 1999. "Integration of Ecosystem Theories: A Pattern". *Ecological Modelling*.117, Issue 1, pp.165-167. Elsevier.
- Martinez-Alier, J. 1987. *Ecological Economics: Economics, environment and society*. Basil Blackwell, Oxford, 286 pp.
- Mora, C.H and De Oliveira, S. 2006. *Environmental exergy analysis of wastewater treatment plants*. Engenharia Termica (Thermal Engineering). Vol. 5 no 2 pp. 24-29.
- Naredo, J.M. and Gascó, J.M. 1994. *Spanish Water Accounts*. OECD. Environment Policy Committee (ENV/EPOC/SE/A(94)2. Paris.
- Rosen, M.A. and Dincer, I. 2001. *Exergy as the confluence of energy, environment and sustainable development*. *Exergy, an International Journal*, 1 pp. 3-13. Elsevier.
- Torres, C and Valero, A; 2007, *Apuntes Termoeconomía*. Universidad de Zaragoza. Spain.
- Szargut,J.; Morris, D.R; and Steward, F.R. 1988. *Exergy analysis of thermal, chemical and metallurgical processes*. New York: Hemisphere. Szargut, J.T. 2003. "Anthropogenic and natural exergy losses (exergy balance of the Earth's surface and atmosphere)". *Energy*, 28 pp.1047-1054. Elsevier. UN-WWAP, 2003. *Water for people. Water for life*. World Water Assessment Programme. United Nations. Unesco.
- Valero, A. 1998. "Thermoeconomics as a conceptual basis for energy ecological analysis". *Proceeding of the 1st International workshop Advances in Energy Studies*. Pp. 415-444. SG Editoriali Padova.
- Valero, A.; Lozano, M.A. and Muñoz, M. 1986. *A general theory of exergy saving, I, II and III. Computed Aided Engineering and Energy Systems: Second Law Analysis and Modelling*, AES. Vol 2-3 Vol. 2-3, ASME Book H0341C. New York.
- Von Spakowsky, M.R. (1986). *A practical generalized analysis approach to the optimal thermoeconomic design and improvement of real-world thermal systems*. Ph.D. Thesis. Georgina Institute of Technology
- Wall, G. 1986. *Exergy -A useful concept*. Physical Resource Theory Group. Chalmers Bibliot. Trick. University of Technology, Göteborg, Sweden 3,4 EOLSS Publisher.
- Wall, G. 2002. "Conditions and tools in the design of energy conversion and management systems of a sustainable society". *Energy Conversion & Managemen*, 43 pp. 1235-1248. Pergamon.
- WHO, 1999. *Environmental Health Indicators: Framework and Methodologies*. World Health Organization. Prepared by David Briggs. University College Northampton, Nene Centre for Research.
- Zaleta-Aguilar, A.; Ranz, L. and Valero, A. 1998. "Towards a Unified measure of renewable resources availability: The exergy method applied to the water of a river". *Energy Conversion Management*. Vol. 39 no 16-18 pp. 1911-1917.

ENVIRONMENTAL IMPACT OF USING DIFFERENT ENERGY SOURCES FOR FAMILY HOUSE HEATING

*Marcin Bukowski, Henryk Manteuffel Szoega**

*Chair of Agricultural Economics and International Economic Relations, Warsaw
University of Life Sciences, Warsaw, Poland*

ABSTRACT

Environmental impacts of using various sources of energy in heating a family house with 180 m² of floor surface were compared by means of the SimaPro computer programme and attached to it databases, describing the environmental impacts of using typical materials and technologies. The set of compared heat energy sources comprised a ground loop heat pump, a liquid gas combustion furnace, an earth gas combustion furnace, a coal combustion furnace, a mineral oil combustion furnace, a wooden pellets combustion furnace, a straw combustion furnace, a wood combustion furnace and an electric stove. After normalisation (which meant recalculating the impacts into their proportions to the average impact of the kind, experienced by an average European in a year), weighting (which meant attaching arbitrary weights to three aggregate impact categories according to a methodology Eco-indicator 99 E/E) and summation of the weighted results expressed in so called ecopoints, the coal combustion furnace turned out to have the greatest impact. It was followed by an electric stove and an oil burning furnace. The wood burning furnace and the heat pump had the smallest impact, almost equal in size. Results indicate that in case of renewable energy carriers like wood, straw and pellets, the total environmental hazard factor is 70% and more is derived from the respiratory harmful inorganic emissions. Extending the analysis by the LCA assessment of equipment (boilers and pumps) might change the order of technologies.

Keywords: family house heating, environmental impact, SimaPro application, Eco-indicator 99 E/E

1. INTRODUCTION

Production, usage, and post-usage waste disposal have their impact on the environment. For an evaluation of such impacts during individual phases of products' life, or an evaluation of the influence of various processes, the Life Cycle Assessment (LCA) method is being applied. This method aims at an identification and hierarchisation of environmental impacts of a product or a process and gives ground for determining ways of minimization of the most adverse impacts. The procedure adopted in the LCA is an analysis of environmental aspects over the whole lifetime of a product or a process, starting from the extraction of raw materials, through production of materials, sub-assemblies and the final product, management of by-products, transportation, distribution, usage, until the final utilization of the post-usage waste. Due to such comprehensive approach it is possible to compare different technologies and select the one with the lowest impact on the environment².

This study compares, using the LCA methodology, nine sources of energy for heating a family house. The following technologies of energy production were compared: a heat pump of water-water type, a wood gasification boiler, a compressed straw fuelled boiler, a wooden pellets fuelled boiler fed by a screw conveyor, a condensation boiler for liquid gas, a low-temperature oil boiler, a coal fuelled boiler with upper combustion system, an electric boiler and a boiler heated with natural gas distributed by a municipal network. Analyses, carried out by using the SimaPro version 7 software, were limited to

* Corresponding author; E-mail: henryk_manteuffel@sggw.pl; Tel. +48 22 5934104.

² Sacrificed to the assessment of environmental impact during the whole lifetime of products and to the comparisons in this respect is The International Journal of Life Cycle Assessment.

the environmental impact assessment of using different energy carriers for thermal energy production. Processes related to the production and the post-usage waste utilization of a boiler and other equipment used for energy production were not included, assuming that those impacts were similar for different energy sources. The influence of infrastructure needed for the supply of individual energy carriers was accounted for as far as it had been included in the databases attached to the application.

2. METHODOLOGY

The present requirements related to the protection of natural environment impose a need of carrying out a complete life cycle assessment of a product, including production, usage and waste utilisation phases [PN-EN ISO 14040... 2009]. Because of the increasing complexity of such analysis computer-aided tools, in particular specially designed software enabling a comprehensive assessment of a process's or product's impact on the environment, play a key role. One of the most popular applications of this type is SimaPro, created by a Dutch company Pré Consultants [Introduction... 2008]. The application estimates damages to environment basing on the estimation of loads attributed to individual categories of influence. This estimation includes also the impacts generated by technological backward linkages of various processes (e.g. transportation needs constructing a vehicle and roads).

An analysis carried out by using the SimaPro software may be divided into three phases:

- defining the goal and scope of analysis
- setting up a data inventory including definitions of individual production processes, definitions of materials used, of types of waste generated and ways of its disposal; in this phase the characteristics of new processes may be created and inserted into the database or characteristics already defined for other projects, stored in the software archives, used
- assessment of the environmental impact consisting in selection of an assessment method, carrying out the calculations and presenting the results in a form of charts and/or tables; impact assessment may be carried out with different methods the software provides for; the selection of method depends mainly on whether it accounts for all types of impact present in a particular case.

The SimaPro software in its version 7 provides a few pre-set environmental impact assessment methods, including CML (invented by the Centre of Environmental Science at the University of Leiden) versions 2000 and 2001, Ecopoints 97 (Swiss Agency for Environment, Forest and Landscape), Eco-indicator 95 and Eco-indicator 99 versions E (Egalitarian), H (Hierarchist), I (Individual) (PRé Consultants, sponsored by the Dutch government), EPS 2003 (Environmental Priority Strategies in Project Design, mainly by Centre for Environmental Assessment of Products and Material Systems, Chalmers University of Technology), IMPACT 2000 (combination of other databases by Pré Consultants), Ecological Scarcity 2006 (an extension to Ecopoints 97), EDIP 2003 (Institute for Product Development, Technical University of Denmark), EDP 2007 (Environmental Product Declarations, composed by Swedish Environmental Management Council) [Introduction...2008]. For the present study, the Eco-indicator 99 method in its E/E version (European Egalitarian) recommended by the software producer was applied.

In this assessment methodology, its authors defined the environment by a set of biological, physical and chemical parameters influenced by human activity and reciprocally influencing the functioning of nature and human beings. Based on this definition three aggregate categories were selected for the assessment of environmental damages:

- human health (HH)

- ecosystem quality (EQ)
- resources (R).

Within each aggregate category a number of detailed categories is included which, when summed up, decide of the volume of aggregated impact. Indicators such as emissions of carcinogens and organic as well as inorganic substances impairing the respiratory system, the depletion of ozone layer, the additional radiation and the influence on climate change are accounted for within the category 'human health'³. Categories of ecotoxicity, eutrophication or acidification and of land use are included into the 'ecosystem quality' aggregate category⁴. The 'resources' category contains the consequences of depletion of minerals and fossil fuels⁵.

Table 1. Annual energy consumption dependent on heating technology

Energy consumption	Energy source								
	heat pump	wood	straw	pellets	liquid gas	fuel oil	coal	electric boiler	natural gas
unit	kWh	m ³	kg	ton	l	l	ton	kWh	m ³
consumption, units per year	2700	22	9087	4.5	2340	1603	4.14	11077	2500

Source: [Manteuffel Szoeg & Olesik 2008].

In order to determine the total impact of a product or a process on the environment, the so called normalization⁶ and weighting⁷ shall be conducted, producing in this way a combined final result expressed in eco-indicator points (Pt). The value of 1 Pt corresponds to a one thousandth of annual environmental load attributable to a European.

An environmental impact assessment of using the nine different sources of energy for heating a family house with 180 m² of floor surface was carried out using the databases attached to the SimaPro software.

The necessary amount of energy or fuel needed for all year round heating of a house was determined basing on heater instruction brochures or branch publications [Laskowski 2006, 2007 and 2008; Małkowska 2006] and by interviewing dealers of heating installations [Manteuffel Szoeg & Olesik 2008] (Table 1). With regard to the necessity that the energy consumption entered as data to the application must be

³ The unit of human health hazard is DALY (Disability Adjusted Life Years), an indicator used for determining the deterioration of human health status. It is measured by the total number of years of human life lost in the consequence of premature deaths or lived in disability as a result of injury or disease.

⁴ In case of ecosystem quality, PDF (Potentially Disappeared Fraction) or PAF (Potentially Affected Fraction) is used as an indicator. It refers to a disappearance of organisms, which, deemed strategic for ecosystem functioning, shall be present in ecosystems in defined amount, and the presence of which is decreased as a result of changes in acidity or amount of nutrients. PDF is also used for expressing an unnatural land occupation and toxic emissions. The multidimensional unit expressing a damage to ecosystem is the PDF related to land area and time (PDF • m² • year).

⁵ The assessment of raw materials consumption is carried out by accounting for both the energy needed for extracting minerals and because of their concentration. The negative impact is expressed by an expected increase of energy consumption (in MJ) in relation to 1 kg of raw material (both minerals and fossil fuels), caused by the deterioration of extraction conditions and the poorer concentration of raw material which will be used as a substitute for presently used raw material after its depletion.

⁶ Normalization consists in dividing an impact by an impact load of a given type experienced annually by one European.

⁷ Weighting is carried out using weights defined by a panel of selected experts, resulting in a hierarchization of the results with respect to their importance for the total environmental impact. For example, when using the Eco-indicator 99 E/E method, the software-suggested weights are 300 for the 'human health' category, 500 for 'ecosystem quality' and 200 for the 'resources' category. These values may be changed by the software user.

expressed in MJ/year (or TJ/year), the consumption expressed in natural units for particular energy carriers was converted into MJ using typical calorific values. In the estimation of waste amount produced during the combustion of different energy materials it was assumed that the ash content in coal is 5%, in wood 1.5%, in pellets 1% and in straw 3.5%. The remaining technologies of heat production were deemed waste-free.

3. COMPUTATION RESULTS

The results of comparisons are presented in Table 2 and Figures 1 through 4.

Results displayed in Figure 1 point out that in case of thermal energy production from non-renewable sources, the highest relative (to the average environmental load experienced annually by a European) impact is noted, no wonder, in the 'fossil fuels' category. It is obvious that using fossil fuels contributes to the reduction of their stock and therefore increases the forthcoming need for swithing to their less energy efficient substitutes. The next in significance respiratory problems are due to emissions of CO. Moreover, the combustion of hard coal has the highest relative impact on the cancer incidence, similar by size only to this of an electric boiler.

Under the Polish climatic conditions the depletion of fossil fuels attributable to the conventional sources technologies can be assessed as really significant, close to, or even surpassing their total average use by a European. This of course should be, for comparison purposes, divided by about four, which is approximately the number of family members in the affluent families that can in Poland afford a house of 180 m² floor surface. Also, it should be noticed that an individual house looses about 4.5 times more heat than an internally situated and 2.9 times more than a collaterally, but not in the first or last floor, situated apartment of equal size in a block of flats, which is a standard way of town dwelling in this country [Pisarski 1996].

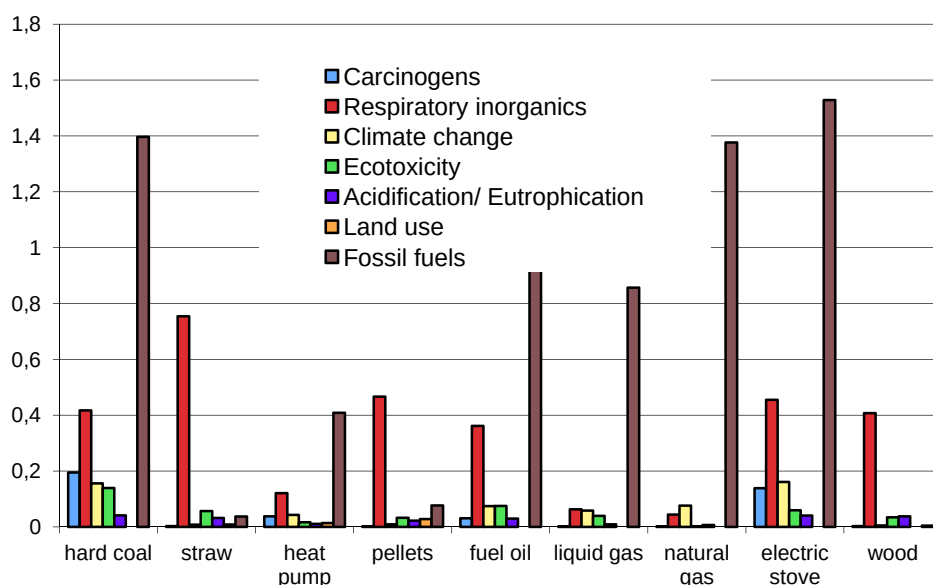


Fig. 1. Comparison of energy sources per environmental impact category after normalisation of individual impacts, Ecoindicator 99 Europe/Egalitarian methodology⁸

A comparison of relative environmental impacts of different house heating energy sources, in three above mentioned aggregate categories is presented in Figure 2. Each time the highest impact was set at 100% and the influence of the other technologies

⁸ Because of insignificant impacts in such categories as ozone layer, radiation, respiratory organics and minerals, they were not included in the presentation of results. In figure 2 they are presented jointly in the 'others' category. The unit of measurement after normalisation is the average annual impact of a given type experienced by (and caused by) a European in a year.

proportionally lower. The impacts are labelled 'relative' because they are compared after normalisation, i.e. after measuring them in units equivalent to the annual average European loads per capita.

In case of 'resources' category, the highest impact is observed for an electric boiler. Combustion of coal and natural gas influences the depletion of natural resources to a slightly lower degree (15 pp). Then come other conventional energy sources like fuel oil and liquid gas. A substantial contribution to the depletion of natural resources caused by an electric boiler, but also a heat pump, is caused by their use of electric power. It was assumed in the model that the electricity comes mainly from coal combustion, which corresponds to the Polish circumstances.

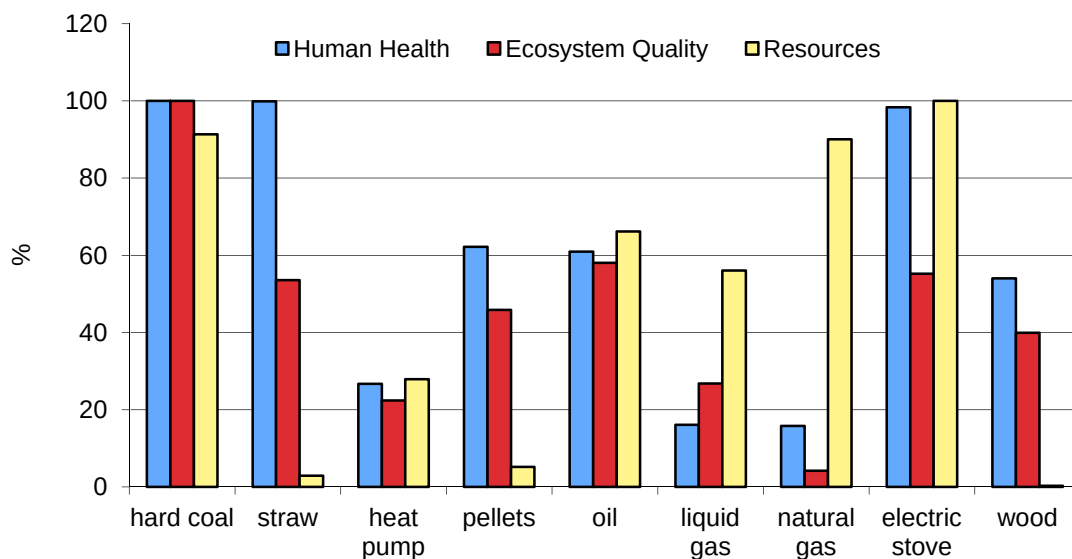


Fig. 2. Comparison of energy sources per aggregate impact category, the highest impact set equal to 100%, Eco-indicator 99 Europe E/E methodology

The highest relative impact on 'ecosystem quality' category is observed in case of coal (100%), and much smaller in case of oil combustion (58%) and in electric stove (55%). A relatively high impact of biomass combustion on ecosystems results from the necessity of introducing into the landscape large monocultural areas. Moreover, using straw for heat production causes its deficiency in agriculture. In accordance with the methodology used for calculations, straw shall be first used for animal production (bedding, fodder) and for fertilizing purposes (ploughing in), in order to keep a balanced content of organic substance in soil.

When analysing the 'human health' category, it can be observed that also in this case the combustion of coal, straw and electric heating have the highest relative impact. Significant influence of using these energy sources on human health results from the emissions of CO, accompanying the combustion of fuels (including coal for electricity generation).

This gas, even in insignificant amounts, blocks the oxygen binding in haemoglobin. Hypoxia, which in an extreme case leads even to death, may occur as a consequence. Technologies based on coal, but also those on biomass burning, defined as emitting substantial amounts of CO, were rated significantly detrimental for human health, in particular because of respiratory problems caused by the emissions of non-organic compounds. In case of biomass combustion the inorganics impairing respiration decide of the negative impact on human health (for straw, pellets and wood their share is 98% approximately). The respiratory impact decided that straw combustion, in view of the model calculations, appeared the most hazardous technology of thermal energy production basing on biomass.

The influence within the categories, then synthesized to a single indicator, is presented in Table 2 and Figure 3, where the results after normalization and weighting are presented. Weighting was carried out using a system of weights from the Eco-indicator 99 E/E methodology.

Table 2. Aggregated environmental impact of using various energy sources in house heating, weighting according to the Eco-indicator 99 E/E methodology, eco-points per annum

Impact category	Energy source								
	hard coal	straw	heat pump	wooden pellets	heating oil	liquid gas	natural gas	electric stove	wood
Total	599.50	287.00	166.97	200.32	394.88	232.53	315.40	581.87	161.20
Carcinogens	58.44	0.70	11.22	0.44	9.25	0.40	0.37	41.52	0.71
Respiratory organics	0.06	0.15	0.02	0.12	0.32	0.22	0.04	0.05	0.04
Respiratory inorganics	125.04	226.13	36.23	139.83	108.39	18.92	13.09	136.51	122.15
Climate change	46.63	2.40	12.84	2.60	22.25	17.50	22.84	48.33	1.43
Radiation	0.00	0.48	1.10	0.16	0.00	0.00	0.00	0.00	0.00
Ozone layer	0.00	0.01	0.04	0.01	0.09	0.00	0.00	0.01	0.00
Ecotoxicity	69.58	28.27	8.08	16.34	37.38	19.69	0.48	29.57	17.18
Acidification/ Eutrophication	20.48	15.80	5.33	11.12	14.91	4.42	3.30	20.17	18.78
Land use	0.00	4.17	6.76	13.86	0.00	0.00	0.00	0.00	0.00
Minerals	0.00	1.47	3.71	0.56	0.00	0.00	0.00	0.00	0.00
Fossil fuels	279.26	7.42	81.65	15.28	202.29	171.37	275.29	305.72	0.91

Source: own calculations.

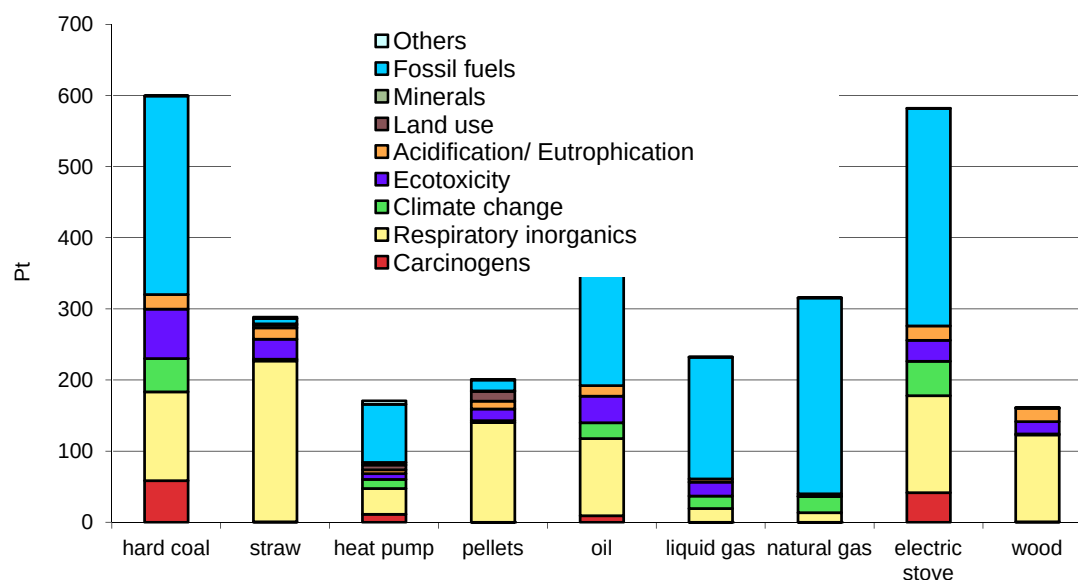


Fig. 3. Comparison of energy sources per impact category and a synthesized single score after weighting, Ecoindicator 99 Europe E/E methodology, division into basic categories, ecopoints

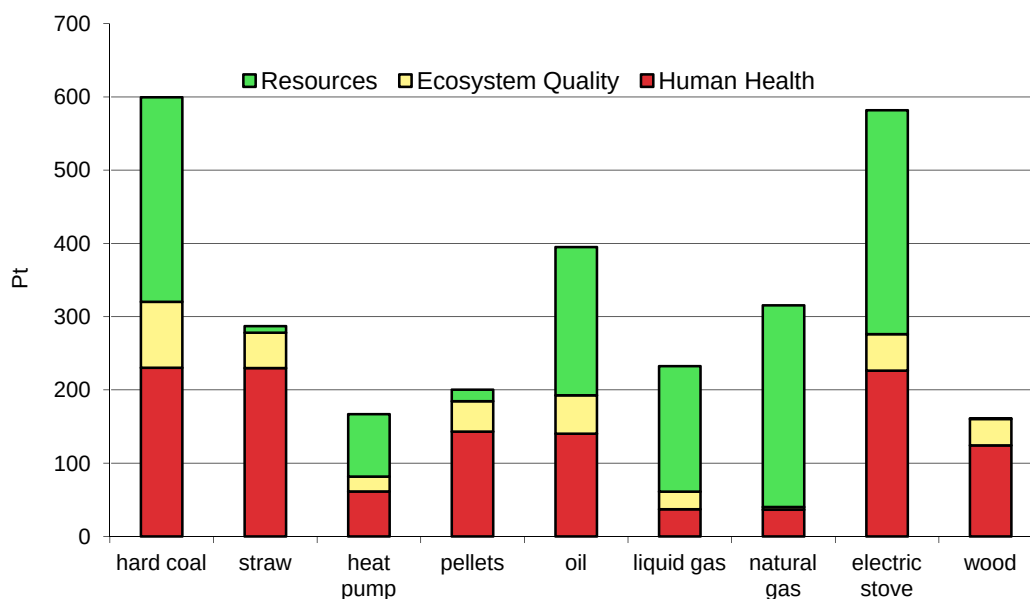


Fig. 4. Comparison of energy sources after weighting, per aggregate impact category and the endpoint (single score) indicator, Ecoindicator 99 Europe E/E methodology, ecopoints

The highest environmental impact is noticed in the thermal energy production as a result of combustion of hard coal (600 Pt) or of using an electric boiler (582 Pt). The wood combustion (161 Pt) and a heat pump (167 Pt) were the technologies with the lowest environmental impact. When compared to traditional electric heaters, heat pumps provide substantial savings of electricity. The Coefficient of Performance (COP) for a typical heat pump varies between 3 to 5 (for electric heaters ~1) which means that more than 70% of heat delivered by a heat pump is produced from the ground-loop source, and the rest from the electric power supply. It must be remembered, however, that in case of a heat pump more severe environmental impacts occur after ending the operation (which was not accounted for in the present analysis). The cooling agent used in a pump, classified among controlled substances, is treated as a hazardous waste and must not be just poured out into a landfill. Similarly, a proper disposal of brine, acting as a frost resistant agent, also poses a problem after ending the operation.

Results of calculations, aggregated into a synthetic indicator denoted in the software as a 'single score' are presented in figures 3 and 4. In case of biomass combustion (wood, pellets, straw) the biggest share in the total impact has the 'human health' category. In case of wood and straw combustion the impact on human health is even more significant than in case of oil and gas combustion. The big impact of these technologies is determined by a significant emission of CO accompanying biomass combustion is the database used by the software.

When comparing the heating by combustion of hard coal with the heating using electric boiler, supplied with electricity also produced by coal combustion, the coal boiler proves to have a higher impact on environment and human health. It is caused by different technologies of energy production. Huge power plants, thanks to protective devices installed (e.g. filters and absorbers) and higher energy efficiency, have a lower impact on the environment, calculated per unit of produced energy, than the household boiler installations.

In case of fossil fuels, the influence on resources depletion is the factor deciding of the total value of eco-indicator. For natural gas, the contribution of this category to the total score is 87%, for liquid gas 74%, and for fuel oil 51%.

4. SUMMARY

The environmental impact assessment of using different sources of thermal energy for heating a house, carried out using the SimaPro software and the Eco-indicator 99 E/E method, has proven that the most harmful for the natural environment method of providing the heating was the hard coal combustion in house installed furnaces. Next to it was an electric heater, where the electricity for powering an electric boiler comes from a coal burning power plant. The combustion of fuel oil appeared to be more harmful for environment than alternative energy sources like combustion of straw, wooden pellets wood or a heat pump. Among the technologies based on the combustion of fossil fuels, the technology of liquid gas combustion appeared to have the smallest impact (Figures 3 and 4). In this case the final result is by 367 Pt (61%) lower than the result received for coal combustion, which supports the EU policy drive to replace coal by gas burning.

Some doubt arises in case of results related to biomass combustion. An analysis of literature does not confirm that biomass combustion is accompanied by such a great amount of CO emissions as it is recorded in the database attached to the software. Presented results, however, indicate that in case of wood, straw and pellets combustion a total environmental hazard is approximately 70% (76%, 79% and 70% respectively) is derived from the respiratory inorganics emissions.

Previous attempts by authors with a somewhat different assumptions gave in certain cases very different results, especially for wood combustion furnaces, which gives rise to a supposition the computation tool used may become relatively easily manipulated by modelling the process or the product analysed [Bukowski & Manteuffel Szoega 2009]. This applies especially to the arbitrary weights used in weighting.

In the comparison limited only to the process of thermal energy production, the lowest environmental impact is caused by a wood fuelled home furnace and a heat pump. Extending the analysis by an LCA assessment of equipment (boilers and pumps) might change the above presented order of technologies.

REFERENCES

- Bukowski M. & Manteuffel Szoega H. 2009, "Oddziaływanie środowiskowe użycia odnawialnych i nieodnawialnych źródeł energii w ogrzewaniu domów mieszkalnych" [In:] *Ekonomiczne uwarunkowania stosowania odnawialnych źródeł energii*. Wydawnictwo Wieś Jutra, Warsaw.
- Goedkoop M. I., Effting S., Collignon M. 2000, *The Eco-indicator 99. A Damage Oriented Method for Life Cycle Impact Assessment. Manual for Designers*. PRé Consultants. B. V. [Available at:] www.pre.nl.
- Introduction to LCA with SimaPro* 2008. PRé product ecology consultants, Amsterdam.
- Laskowski P. 2006, *W czym palić?*. Murator no 9.
- Laskowski P. 2007, *Jaki kocioł wybrać?*. Murator no 1.
- Laskowski P. 2008, *Ile za ciepło?*, Murator no 10.
- Małkowska I. 2006, *Kocioł na miarę*, Budujemy dom no 7-8.
- Manteuffel Szoega H. & Olesik L. 2008, "Technology Dependent House Heating Costs" [In:] *Towards a holistic approach based on science and humanity. 6th Biennial International Workshop Advances in Energy Studies*. Graz University of Technology, Graz.
- Pisarski M. 1996, "Energooszczędność i estetyka w budownictwie wiejskim" [In:] *Ochrona i zrównoważony rozwój środowiska wiejskiego*. Warsaw Agricultural University Press, Warsaw.
- PN-EN ISO 14040 lipiec 2009. *Zarządzanie środowiskowe. Ocena cyklu życia. Zasady i struktura* 2009. Polski Komitet Normalizacyjny, Warsaw.

SESSION 2.1

EVALUATING ALTERNATIVES TO FOSSIL ENERGY

Dittmar M.

NUCLEAR ENERGY: STATUS AND FUTURE LIMITATIONS

Nonhebel S.

ON THE COMPETITION BETWEEN FOOD, FEED AND FUEL

Li X., Hubacek K., Siu Y. L.

WIND POWER IN CHINA: DREAM OR REALITY

Raugei M., Fthenakis V., Fullana-i-Palmer P.

DISPELLING THE MISCONCEPTION OF LOW-EROI PHOTOVOLTAICS: PEAK OIL IS HERE, LET US NOT SQUANDER WHAT IS LEFT

NUCLEAR ENERGY: STATUS AND FUTURE LIMITATIONS

*Michael Dittmar**

*Institute of Particle Physics, ETH Zurich
8093 Zurich, Switzerland*

ABSTRACT

Discussions about the origin of energy in a post fossil fuel world are quickly dominated by a general exchange of mostly fruitless arguments about the future contribution of nuclear energy. In this paper we discuss the status of nuclear energy today and analyze its potential evolution during the next 10-20 years. The facts are that nuclear energy contributes only about 14% of the world's electric energy mix today, and as electric energy contributes itself only about 16% to the end energy use, its contribution is essentially negligible. Still, nuclear energy is plagued already with a long list of unsolved problems. Among the less known problems one finds the difficulties that nuclear plants can not provide power according to needs, but have to be operated at full power also during times of low demand. As a result, regions with large contributions from nuclear power need some backup hydropower storage systems. Without sufficient storage capacity, cheap electric energy is suggested during low demand times, which obviously results in wasteful applications. The better known problems, without solutions since at least 40 years, are the final safe storage of the accumulated highly radioactive nuclear waste, that uranium itself is a very limited and non renewable energy resource and that enormous amounts of human resources, urgently needed to find a still unknown path towards a low energy future, are blocked by useless research on fusion energy. Thus, nuclear energy is not a solution to our energy worries but part of the problem.

Keywords: Limits of Nuclear Energy, Fusion Illusions, Uranium Peak and shortages

1. INTRODUCTION

Commercial nuclear fission energy started during the cold war period in the 1950ies. The nuclear energy sector has always been plagued with its dual role in building up a huge overkill nuclear weapon capacity for a few countries and as being praised for its final solution to the energy problem. More than 50 years later, and about 20 years after the cold war has ended, the promised nuclear solutions to the energy problems are further away than ever imagined and the nuclear weapon sword of Damocles (a final solution) is still above us. During the last few years the energy debate started to heat up again and so did the question about the future of nuclear fission energy. Perhaps one of the most remarkable observations by the International Energy Agency (IEA) at the end of 2008 was that the current world energy system is unsustainable. This statement was made in connection to the presentation of their annual world energy outlook up to the year 2030 [IEA08] and with respect to the use of fossil energies. According to the counting scheme of the IEA, used by many other organizations, energy data are presented in units of the required amount of oil equivalent. Unfortunately, this scheme leads to an overall distortion in the non fossil energy sector, favoring nuclear power by an unjustified factor of three. As a result, the contribution from nuclear energy to the world energy sector is accounted for as about 7%, while hydropower is presented with a contribution of only about 3%. However, a more careful analysis of electric energy data reveals that during the year 2009 hydropower contributed about 3000 TWhe, while nuclear fission power contributed only

* E-mail: Michael.Dittmar@cern.ch

2560 TWhe. A more accurate world energy accounting system would perhaps be slightly more complicated, but it would allow to make more realistic estimates of the impacts from the coming decline of oil and gas. One would thus first separate electric energy, which makes 16% of the current world energy mix, from the other demanded forms of energy for transport, heating and other uses and secondly argue about the possibility to transform electric energy efficiently back into the other required forms. Furthermore, a realistic analysis of the contribution of nuclear energy should also mention the problem that nuclear power plants can provide essentially only base load power, while electric energy coming from hydropower and gas fired power plants has a much higher value, as production can follow the huge demand variations for electric energy. Thus, in fact nuclear produced electric energy should receive some kind of penalty factor in comparison with hydropower. Ignoring such details, one calculates easily that nuclear energy contributes currently only an almost negligible amount of about 2.3% to the worlds useful end energy. Taking the European Union as an example of an industrialized area, one finds that the contribution of electric energy is about 23% from which nuclear power plants contributed about one 25% in 2009. It follows that even with a relatively large density of nuclear power plants, they hardly contribute 6% to the European energy system. These sobering facts about today's small contribution of nuclear fission energy indicate already that nuclear energy cannot contribute in any significant way during the next decades to compensate for the coming decline of fossil fuels.

Still, it is important to determine, with some realism, an upper limit for the contribution of nuclear energy during the coming decades. Such limits come from the technological and political constraints to construct new nuclear power plants and from the limits to extract uranium fuel. In the following we present some details about the current and near future situation with nuclear power and describe why one should not count on technological miracles with respect to future fission and fusion reactors. We conclude this paper with some arguments, which demonstrate that nuclear energy should be considered as an integral part of our energy problem and not as a possible solution. It turns out that, even if the Nuclear Armageddon can be avoided, many potential problems with the existing nuclear energy infrastructure, starting from the fuel production to the final waste deposal might soon become important regional and essentially unsolvable nightmares for the concerned future generations.

1.1 Nuclear Energy today

The commercial use of nuclear fission energy started some 50 years ago. Today 441 nuclear power plants in 30 countries with a total electric capacity of 374.6 GWe are considered as operational. These reactors provided 2560 TWhe of electric energy in 2009, about 1.6% lower than in 2008 and about 100 TWhe lower than in the record year 2006. About 84% of these nuclear produced electric energy comes from 344 reactors, with a capacity of about 315 GWe, operated in the relatively rich and highly industrialized OECD countries in Western Europe, North-America, Japan and the Republic of Korea.

Some nuclear energy saturation effects and even declines due to their aging reactors are observed for the OECD regions and still no real replacement policy for the relatively important amount of nuclear produced electric energy has been found. The existing reactors have an average age of about 25 years and about 100 reactors are expected to reach the retirement age during the next 10-15 years. Many of them will certainly be terminated during that period.

The picture is drastically different when one looks in which countries the 60 reactors, currently under construction, are located. Most of them are found outside of the OECD block and in the larger so called emerging countries, e.g. countries with a predicted continued fast economic growth.

Thus, on one hand a stagnation of nuclear power in OECD countries is observed and on the other hand one finds very ambitious plans for new nuclear reactors in China, Russia and India. These plans seem to have some parallels with similar past aggressive

nuclear growth scenarios in the OECD countries, following the political oil crisis during 1973. The fact that not even 50% of these aggressive nuclear growth scenarios were realized in the past is a warning for those who believe in today's predictions about strong nuclear growth scenarios. Thus, and independently of the realization of the ambitious plans of China, Russia and India, a further slow decline of nuclear energy during the coming decades and in the rich OECD countries, appears to be essentially unavoidable.

2. LIMITING FACTORS FOR NUCLEAR FISSION ENERGY DURING THE NEXT DECADES

As presented above, the often mentioned coming nuclear renaissance, can only come from China, Russia and India. Taking China as an example one finds that nuclear power currently plays an almost negligible role: the 12 nuclear power plants in China with a capacity of 9.6 GWe produced 65.7 TWhe in 2009, about 1.9% of the total electric energy. Following its economic success and the accumulation of up to about 1000 billion dollars, China is now in a position to simply buy -- in the "free market" -- many high tech items like nuclear power plants, large amounts of uranium and many other vital resources. Since China now faces enormous environmental problems created by their extensive use of dirty coal, the option of increasing nuclear power production appears to be logical. In addition the operation of nuclear energy is still considered as one of the most obvious signs for a successful transition to a modern society. The result is that out of the 60 nuclear power plants currently under construction 24 are found in China. If their construction proceeds according to plans about 2-3 GWe of new capacity will be added per year up to 2012 and another 6-7 GWe per year from 2013 to 2015. Plans exist to continue this growth with 33 more reactors by 2020 and another 120 reactors for the years 2020 to 2030. According to the latest plans, the nuclear power capacity should reach about 35 GWe by 2015, 80 GWe by 2020, 200 GWe by 2030, roughly twice the number in the USA today, and perhaps even 400 GWe by 2050. These plans require corresponding large amounts of uranium, starting with a demand of 2875 tons in 2010 to perhaps 6000 tons by 2015, 14000 tons by 2020 and 30000 tons by 2030. However, the 2009 uranium mining in China produced only 750 tons and without any significant uranium deposits of its own, China investigates aggressively in existing and planned uranium mines all around the world.

This situation raises the question about uranium resources and uranium mining: will these mines be capable to double the current uranium mining from about 51 000 tons in 2009 to more than 100 000 tons during the next 10 to 15 years?

Before going into some details, we would like to remind the reader that already the small contribution from nuclear power plants to the world electric energy of 14% requires an amount of about 68 000 tons of natural uranium equivalent per year. However, during the last 10 years only between 65-75% of this uranium was provided from uranium mines and the rest came from so called secondary resources, accumulated mainly during the cold war period between 1950-1990 and a smaller contribution from expensive nuclear fuel recycling and depleted uranium tails. All available data about uranium mining, collected in a bi-annual publication, the Red Book[RB09], from the International Atomic Energy Agency (IAEA), indicate that the so called civilian part of the secondary resources has essentially been exhausted. In contrast, about 200 000 tons and 300 000 tons remain in the military reserves of the USA and Russia respectively. Some rough estimates allow to assign an amount of about 100 000 per country, fixed in the remaining 20 000 nuclear warheads. Most likely another up to 100 000 tons per country is considered to be in weapon ready highly enriched weapon grade uranium, not directly useful for the existing nuclear reactors. It might thus be possible that especially Russia controls some relatively large amount of uranium, ready to be injected into the international uranium market.

According to the 2009 edition of the Red Book (RB09), new large uranium mines with a production capacity of more than 2 000 tons are supposed to start during the next 5

years in Kazakhstan (plus 10 000 tons), Namibia (plus 9 200 tons), Niger (plus 5 000 tons), Canada (plus 6 900 tons) and Jordan (plus 2 000 tons). The total production capacity of the 9 larger mines adds up to 33 000 tons by 2015. In addition, many smaller mines with capacities between a few hundred to 2 000 tons will open in several countries, adding perhaps another 16 000 tons of capacity by 2015. Assuming that the existing capacity, given for 2010 as 70-75 000 tons, will not be subject to significant declines, the authors of the Red Book 2009 estimated the total maximum uranium mining capacity for 2015 to be between 96 000 tons and 122 000 tons. The predicted spread indicates large uncertainties about the new projects and the date when full capacity can be reached.

When looking further into the future, one finds an interesting prediction made by the authors of the Red Book. It is stated that the worldwide uranium mining capacity is expected to reach a peak with a maximum between 98 000-141 000 tons around the year 2020, followed by decline to 80 000-129 000 tons (2025), 75 000-119 000 tons (2030) and 68 000-109 000 tons (2035). As if these numbers would not be surprising enough, the ones given for Kazakhstan can perhaps be called alarming. A peak production of 28 000 tons is expected already around the year 2015, followed by a decline to 24 000 (2020), 14 000 tons (2025), 12 000 tons (2030) and to only 5 000-6 000 tons by 2035.

The authors of the Red Book acknowledge that the uranium mining capacity numbers are very different and always much higher than the real production from mining. In order to quantify the difference, one can confront the predicted mining capacity numbers from past editions for the year 2010 with the almost known mining result. Accordingly, past capacity predictions for the year 2010, were 69 000-83 000 tons (RB05) and 81 000-96 000 tons (RB07). In comparison the latest and naturally more accurate RB09 estimate for 2010 presents a capacity between 70 000-75 000 tons, about 11 000-21 000 tons smaller than the RB07 prediction. It follows that roughly 50% of the new projects have been delayed or "evaporated" between these two editions. In addition and according to the latest estimates, uranium mining in 2010 is expected to reach about 55 000 tons. The real mining is thus 15 000-20 000 tons, or 20-30%, smaller than the mining capacity figure given in the just published RB09 report.

In chapter I of "The future of nuclear energy" from 2009 [Dittmar09], we had presented two scenarios, A and B, to guess the future evolution from past trends. According to scenario A, which assumes that about 75% of the Red Book 07 capacity can be realized, a 2010 estimate of 60 500-65 000 tons was obtained. For scenario B it was assumed that the existing mines continue their annual production of 40 000 tons (roughly the 2005 result) and that only 50% of the new mines can be realized in time and a forecast for 2010 of 53 000-55 000 tons was obtained. Scenario B is thus in agreement with the 2009 and most likely also with the 2010 result. Following the same procedure to estimate the uranium production for the year 2015, using the RB07 capacity estimates, the predictions were 72 000-88 000 tons (scenario A) and 61 500-70 000 tons (scenario B). If one uses the RB09 capacity estimates for the year 2015 and takes the 2009 mining result of 50 000 tons as an updated baseline, the expected 2015 mining would be 72 000-91 000 tons (Scenario A) or 68 000-78 000 tons (Scenario B).

In addition to these two scenarios my own 2009 guesstimates, assumed that uranium mining will be strongly affected by the financial crisis and by the increasing troubles to exploit lower and lower grade. My scenario was wrong for Kazakhstan during 2009 and 2010. However, the almost too perfectly matching of the yearly mining in Kazakhstan with the plans from the past years, remind a critical observer about the "false" success stories of some historical 5-year plans in the Soviet Union. One might thus remain a little "uneasy" about the mining reports from this area. In contrast to this particular country, my last year guesstimate was in rough agreement with the mining results from all other countries in 2009 and presumably also with the one in 2010. Therefore, and despite the fact that my 2009 uranium mining estimate was 7000 tons too low, my 2010 updated guesstimate for the next years is that uranium production from all countries, other than Kazakhstan, will not increase significantly above 40000 tons during the coming five years. I thus continue to predict problems with uranium supply and

assume that shortages after 2013 can only be avoided if new "miracles" (at least for me) will happen. Examples of such "miracles" are that uranium mining in Kazakhstan can really be further increased to the claimed 24000 tons by 2015 or that a new deal concerning the military uranium reserves between Russia and the USA will be made in time.

Whether and how the future uranium needs of China and India can be satisfied -- even if almost all future production went to these countries -- remains to be seen. If these needs can not be satisfied, perhaps their dreams of becoming rich industrialized countries, thanks to billions of dollars spent on nuclear power plants, will end in nightmares with unfinished or unfueled plants lying in ruins.

One should also reflect about the possible consequences from the unavoidable decline of oil on uranium mining. For example one could think about the impact of a deep economic crisis on many essential parts of the uranium fuel chain. If history can be of any guidance in such a situation, one might conclude that uranium mining will decline in all the affected countries. Furthermore one could guess that the "best" nearby friends will be served first. Thus one could imagine that uranium from Canada might go to the USA and the one from Australia and Kazakhstan to Russia, Japan, Korea and China. It is of course uncertain if sufficient amounts can be extracted and delivered even for the nearby countries. Such a situation would look especially difficult for the requirements of Western Europe. Most likely only a tiny fraction of the required uranium would reach Europe under such a scenario and the results would be that the stability European electric grid would quickly end.

3. WHY WE SHOULD NOT COUNT ON MIRACLES FROM FUTURE FISSION AND FUSION REACTORS

While it is acknowledged in general that fossil fuels are finite, most people think that potential problems are still a few generations away and that nuclear fission and fusion energy, following some decades of research and technology, will be the solution. Following the often expressed idea that known conventional uranium resources can satisfy the current yearly requirements for up to about 100 years the situation seems to be under control. However, it has not gone totally unnoticed that the current real nuclear contribution to the final energy mix is tiny and that some nuclear growth scenario needs to be taken into account.

Taking for example the current maximal nuclear growth scenario from the RB09 of perhaps 2% as a guideline, by 2030 nuclear energy would still provide only about 20% compared to the world electric energy supplied in 2009. Taking a more aggressive growth scenario of 5%/year, e.g. a doubling time of roughly 14 years, nuclear energy would reach today's total electric energy numbers by roughly 2050, thus about 1/4th of today's total amount of energy. With today's type of reactors about 500 000 tons of uranium would be required on an annual basis. As a result the claimed to be known exploitable uranium resources in the ground would of 6.3 million tons [RB09] would already be exploited at latest around 2046 in the 5% growth scenario. Still, even with the moderate 2% growth scenario the resources would be terminated quickly and uranium mining would end around the year 2065.

Of course such scenarios are totally unrealistic as uranium mining like any other mineral will follow some kind of Hubbert exploration curve. Nevertheless, the problem of limited uranium resources is in general being accepted by the nuclear energy lobby and has been summarized in the so called Generation IV nuclear power plant road map towards the development of safe fast breeder reactors [GenIV]. According to the roadmap from the year 2001 the new reactors should be ready for commercial construction around the year 2030.

Fast reactors are operated with the prompt neutrons from the nuclear fission and can be considered as prototypes for future Generation IV reactors. Among them is the

French Phenix reactor, originally a 0.2 GWe prototype breeder reactor, which started operation in 1974. This reactor was finally closed in October 2009 and officially terminated in February 2010. One might hope that a detailed review of its past operation, allowing verification of the so-far unsubstantiated claims about nuclear fuel breeding, will be published eventually. Another fast reactor is the Russian BN 600, a 0.56 GWe reactor, operated since 1981. This reactor has just received the permission to continue its operation for 10 more years. The construction of its newer and slightly larger version, the BN 800, was started during 2006 and following some delays is currently expected to begin operation in 2014 at earliest. According to the WNA document [WNA1], both Russian reactors are now called "fast reactors" instead of "fast breeder reactors". The last "just functioning" fast breeder prototype is now the Japanese Monju reactor with a capacity of 0.28 GWe. It has, after a 15-year-long stop, officially begun to operate under test conditions this spring and is supposed to reach its normal operation only by 2014. According to the Japanese nuclear agency the date for the operation of commercial fast breeders is now given as 2050. This is not very different from statements of French government officials claiming that the next commercial breeder reactor will not be operational before the year 2040. Thus, the original timeline of 2030 for the Generation IV reactors appears to be totally outdated.

Not much experimentation with respect to thorium reactors has been reported during the past years. However, the program to develop a high temperature high efficiency pebble bed thorium reactor project in South-Africa has been stopped. It follows that those who hope for future TH232 breeder reactors are left with nothing but modeling to support their hopes. Taking the current financial world crisis into account, the construction and realization of thorium prototype reactors during the coming years does not look very promising. Finally, newspaper reports about future "small" scale wonder nuclear reactors appeared during the past months, claiming that such projects are supported by some rich private promoters and also by the US and Russian governments. However, looking at similar claims and plans from past decades one might give them not much more credibility than most people give to snake oil medicine.

Having seen that even the most optimistic hopes for a nuclear fission renaissance are faced with enormous fundamental problems and that such hopes are still far below any realistic replacement for the coming decline of fossil fuels and especially of oil, expected to decline during the next 5-10 years. The last hope, for an economic growth based society, is thus put on nuclear fusion energy and its flagship ITER, currently under construction in Southern France. The 2009 and 2010 news about the ITER project, known also as the path to commercial nuclear fusion energy, a multi billion dollar/euro dream project of all larger countries, demonstrate that it is becoming nothing short of a financial nightmare for high level powerful bureaucrats and politicians in Brussels and elsewhere. Reasons for this nightmare are many:

The exploding cost of the project now admitted to have increased, even before real construction has started, by almost a factor of three. Claims are made, and even transmitted by project officials that ITER became so expensive because it has been set up as an international project. Certainly not a good start for a project defined to pave the path towards fusion energy.

(Doubtful) Statements by scientists and politicians that alternative and much more promising directions need to be taken towards mastering nuclear fusion. Examples are the multi billion euro laser fusion projects in the USA, the UK, France and elsewhere as well as special agreements like the one between Russia and Italy on alternative costly fusion projects. Obviously such projects raise doubts about the scientific foundations of the ITER project.

The distribution of the knowledge that the ITER project has absolutely nothing to do with commercial energy production and that, even if realized according to plans, not even some of the most basic tests required for a future even bigger fusion project can be performed. Among these tests one finds the demonstration that the tritium breeding chain can function and that a neutron radiation resisting material, which at the same time can

survive the always occurring plasma eruptions, can be found. These and other fundamental problems have been explained in detail in the article "Fusion Illusions"[Dittmar08] and in Chapter IV [Dittmar09]. As explained, enough knowledge about the imagined tritium breeding process, required for a future commercial power plant, has already been accumulated. It is thus understood that nobody within the fusion community has even the slightest idea on how this problem can be solved. One can be sure that once this still-well-hidden problem becomes common knowledge, the enthusiasm from the entire scientific community will disappear quickly.

The recent statement from French physics Nobel laureate G. Charpak and other scientists, asking for an end of the ITER project and for the transfer of the money to more down-to-earth nuclear fission projects, must hit extremely hard in the country where most of the money has to come from.

The year 2010 might not be the termination year of the ITER project, but perhaps it can be defined as the year when the "false dawn" of nuclear fusion was realized. We can thus safely predict that the belief in commercial nuclear fusion on our planet will end once the younger generation of scientists sees that plasma fusion research is a dead end career path and turns its talents to other research projects.

4. CAN WE UNDERSTAND NUCLEAR ENERGY AS PART OF THE ENERGY PROBLEM BEFORE POTENTIAL NIGHTMARES TURN INTO THE GREATEST DISASTER EVER

As we have explained above, commercial nuclear energy is currently contributing only a tiny fraction of about 14% (and only 2.3% to the final useful energy mix) to the worldwide electric energy mix. Still the nuclear reality in many rich countries of the OECD block demonstrates that it will be essentially impossible to keep their current nuclear energy capacity from slowly declining during the next decade. Current hopes from nuclear energy believers, often expressed in our Western media, are thus based on plans in China, India and Russia. Could it perhaps be possible that such statements about the nuclear renaissance are made with the hope that a few Western companies, with the nuclear power plant construction know how, can sell such nuclear power plants in exchange for hundreds of billions of dollars accumulated by China (and soon India and Russia) during its past years of economic boom? While this idea might be too far fetched, it would at least explain why the acknowledged stressed uranium supply situation during the coming years is almost never discussed in the corresponding articles.

This idea might remind us, in the richer countries, about the legacy of past and still ongoing mega-projects, which are all based on the assumption that a continuous growth of oil, gas and energy in general supply will be possible during the coming decades.

In contrary to such "growth based" illusions, one observes that more and more people start to think about the problems related to the limits of exponential growth on a finite sized planet. While it is already very late to start planning for the coming unavoidable contraction of economic activities and the subsequent collapse of vital infrastructures, it is certainly a better option to try some planning instead of just waiting for the coming chaos resulting possibly into some future resource wars.

In summary of the current nuclear energy situation and with respect to the unavoidable decline of oil we conclude that:

1. Nuclear energy, with its current contribution of about 14% to the world electric energy, cannot be increased in such a way that it would compensate for the decline of fossil fuels at any significant level.
2. The average reactor age of above 25 years will result in the termination of up to 100 reactors during the coming 10-15 years, mostly in Western Europe, North-America and Japan. As most of the future reactors, currently under construction or in the

planning phase, are found in China, Russia and India, nuclear energy in the richer OECD countries will decline.

3. Problems with the coming more and more limited supply of oil will lead to price explosions and suspensions of all kind of future mega projects. Unfortunately this will also affect heavily the necessary, but not even started, deep underground project needed for a safe storage of the highly radioactive nuclear waste and for a safe decommissioning of retired nuclear power plants. Even though little is known today about how and where to construct final nuclear waste deposits, the problem can not expected to disappear magically during the coming years. One can expect that the current situation will lead most likely to a nightmare scenario. Such a scenario would mean that future low energy societies will not be able to deal with the problem anymore and that the radioactive material will slowly be mixed to the surroundings, resulting into some heavily contaminated areas for hundreds to thousands of years.
4. Thus, even under the unlikely situation that from tomorrow onwards one would be able to plan and act for a "power down" path in our societies, one will be faced with a dual problem of bad options: (a) keeping the electric grid functioning as long as possible requires the further running of the still reliable functioning nuclear power plants. Thus one could imagine that the huge amount of accumulated nuclear weapon arsenal could be eliminated in such a way. Unfortunately this burning would produce even more nuclear waste for future generations. The alternative (b) would be to degrade the highly enriched uranium back to natural levels, followed by its burying together with the already accumulated nuclear waste and as quickly as possible. Unfortunately this is a very costly option and one without a guarantee that the deep mines will be sufficiently safe.

Both options are not perfect but certainly much better than the final ultimate use of the Nuclear Weapon arsenal, still ready to solve the problem, that the homo sapiens was perhaps an evolutionary mistake. Of course such a final solution would result in a huge "collateral damage" and would eliminate certainly a countless number of other species for ever.

In summary we have presented hard and unpleasant facts about nuclear energy, which demonstrate that nuclear fission power is an integral part of our energy problem. Unfortunately the false hopes in a solution coming from the mastering of the nuclear fission and fusion energy technology, especially within the scientific community, are still large.

These false hopes are still hiding very efficiently the view towards urgent plans and the necessary first steps into the unavoidable end of our energy growth addicted way of living.

ACKNOWLEDGEMENTS

Even though the views expressed in this paper are from the author alone, I would like to thank several colleagues, friends and many students who took the trouble to discuss the subject during the past few years with me. I would like to thank especially W. Tamblyn for many valuable suggestions and his careful reading of parts of this paper draft. I would also like to thank S. Newman and Prof. F. Cellier for their encouragement to write the longer reports about nuclear fission and fusion energy, which formed a solid basis also for this report.

Thus, the author hopes, with the ideas expressed in the quote from Gustave Le Bon below, that this report will contribute to the realization of some kind of "telescope", which will help others to observe that some objects are moving around the Jupiter.

"Science promised us truth, or at least a knowledge of such relations as our intelligence can seize: it never promised us peace or happiness".

REFERENCES

- [IEA08] For the *IEA world energy outlook 2008* see the presentation at <http://www.oecd.org/dataoecd/45/29/42414080.pdf>.
- [RB09] *The 2009 edition of the bi-annual Red Book from the IAEA* and the NEA was published on July 20, 2010. The corresponding press release to the report and further references can be found at <http://www.nea.fr/press/2010/2010-03.html>.
- [Dittmar09] The report "The Future of Nuclear Energy" in four chapters from 2009 can be found at <http://europe.theoildrum.com/node/5631>; 5677; 5744 and 5929.
- [GenIV] Details about the *Generation IV International Forum (GIF)* can be found at <http://www.gen-4.org/>. The detailed roadmap program is presented at <http://www.gen-4.org/Technology/roadmap.htm>.
- [WNA1] The statements that the Russian Fast Reactors are not breeder reactors but simply burners with fast neutrons can be found in the WNA article about Russia at <http://www.world-nuclear.org/info/inf45.html>.
- [Dittmar08] The original article "Fusion Illusions" is published in the second edition of the *The Final Energy Crisis* edited by S. Newman. For more details and many other articles about the coming energy crisis, cf. <http://candobetter.org/TFEC/>.

ON THE COMPETITION BETWEEN FOOD, FEED AND FUEL

*Sanderine Nonhebel**

*Center for Energy and Environmental Studies
University of Groningen, The Netherlands*

ABSTRACT

In climate policies in the developed world the use of biomass as an energy source plays an important role. Indications exist that these policies are affecting global food security. In this chapter we compare the global demands for food, feed and energy in the near future. We distinguish between developing countries, transition countries and the developed countries. The first group of countries needs extra food for their growing population, the second one needs extra feed, since the increased incomes among their population lead to increased demand for animal products. The developed countries require biomass to reduce the CO₂ emissions of their energy use. On global scale the extra needs for biomass as a fuel (1100 MT) turn out to be larger than the extra needs for food and feed (800 MT each). This huge demand for biomass from the energy system is likely to result in large instabilities on the international agricultural markets.

Keywords: biofuels, food security

1. INTRODUCTION

Two years ago (2008) world market food prices reached highest levels ever, leading to increased costs for food and food security problems in the third world. FAO reported food riots in 33 countries and estimated that 75 million people became food insecure over and above the 850 million in the years before. Later that year food prices dropped again and presently food prices are relatively low (FAO, 2009). Frequently mentioned reasons for the 2008 high prices pointed to shortages on the world market due to lower yields in main exporting countries, increased demand for livestock feed in Asia and increased demand for biofuels in the US and EU (Troostle, 2008).

The increased demand for biofuels in OECD countries is the result of Climate Policies developed in these countries (FAO, 2008). Energy from biomass is considered to be climate neutral and in many national climate policy plans the use of biomass as energy source plays an important role. The EU directive on renewable energy, for example, mentions that 10% of all transport fuels should be from biomass by the year 2020 (FAO, 2008). (The present contribution is less than 1 %) The fact that organizations like FAO and OECD mention the use of maize as feedstock for biofuels in the US as one of the causes for the large disturbances in the global food market makes it interesting to analyze the magnitude of needs for crops for fuel in relation to the need for crops for food and livestock feed on a global scale. When the present very small use already affects food security situation in Africa and Asia the energy policies aiming at 10% biofuels in 2020 might have disastrous effects on global food security.

In this paper we determine the demands for food, feed and fuel in the coming decades and compare the order of magnitude of these demands. With respect to global demands for food three different factors are of importance: the size of the global population (more people need more food), the type of diet of this population (luxurious diets require more resources than basic menus) and the use of cereals as source for biofuels. These factors show different patterns in time and space. To understand the processes behind these demands the needs for food, feed and energy are first discussed in historical perspective on the global level, then the differences between various

* E-mail: S.Nonhebel@rug.nl; Tel. ++31 503634611

countries are analysed. With this knowledge a very simple model is constructed to determine present and future needs for food, feed and fuel. The model results are compared with the present situation on the global cereal market, and consequences of present Climate Policies in OECD countries for food security in the developing countries will be discussed.

2. FOOD DEMAND

The main driver for the global demand for food is the size of the population, increase of the population leads to an increased demand for food. Figure 1 shows the global population from 1750 onwards.

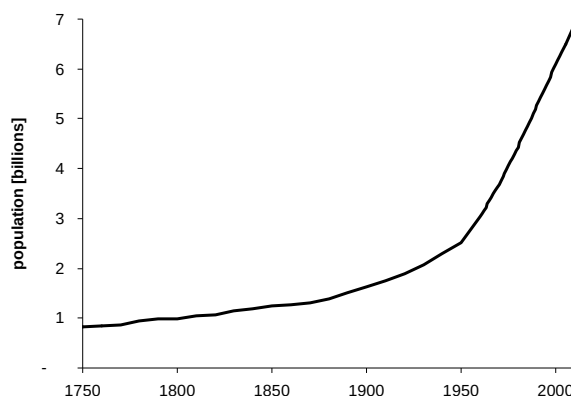


Figure 1. World population from 1750 onwards (Evans 2001)

In 1750 the global population was less than 1 billion people, it doubled in the next 200 years up to 1950 and from then on steep increase was observed, it nearly tripled in 50 years. In these 250 years food production sector was able to feed this increasing population. Up to the 2 billion people the increased need for food was fulfilled by increasing the area under cultivation. Later on the green revolution with the improved crop varieties, application of fertilizer and pesticides etc, led to large increases of the crop yields per hectare and area under agriculture remained the same (Evans 2001).

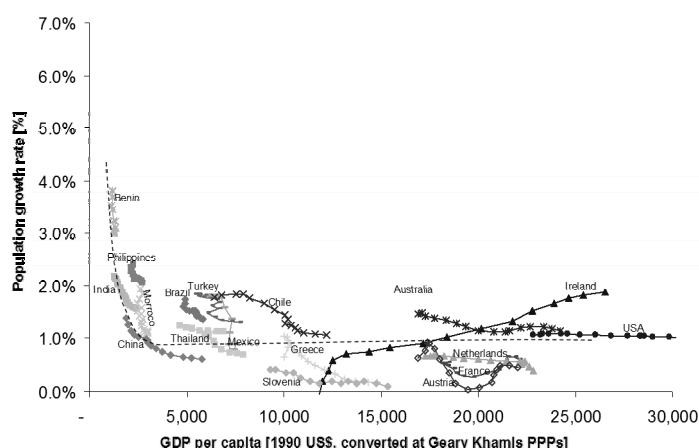


Figure 2. Population growth as function of GDP per capita. Dotted line shows general pattern used in this paper. (Data are for the years 1990 – 2005; sources FAOSTAT, 2007; GGDC, 2007).

Presently large differences between individual countries can be found with respect to population growth. To give an indication of the differences figure 2 shows the population growth for a large variety of countries from very poor countries in Africa to the rich countries in Europe. The GDP is used as indication for the development of the

countries. The rich countries are on the right hand of the graph and the poor countries on the left hand.

The graph shows that in the developing countries population growth is around the 2-3 % per year, it declines rapidly with increasing GDP and levels off around 1% in the rich western countries. It should be noted that population growth is plotted here, not birth rates. The increase in Ireland over the last 15 years is mainly caused by Irish returning back to Ireland, after having left for the US in the economical crisis in the 1980-ties.

2.1 Demand for meat and livestock feed

Presently over 35% of the cereals produced in the world is fed to livestock (USDA, 2007.). Meat consumption plays an important role in global demands for cereals. Figure 3 shows the global meat consumption from 1960 onwards. In the last 50 years annual the meat consumption increased from 70 to 250 MTon per year. The steep increase was mainly due to increased consumption in the developing world, since meat consumption in the rich countries was more or less stable since 1985.

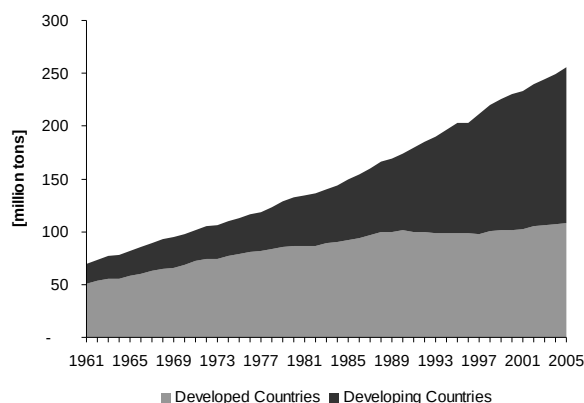


Figure 3. Trends in global meat consumption (source: FAOSTAT)

The feature of stabilizing meat consumption in Western Europe and USA can also be recognized in figure 4. This graph shows the changes in consumption of animal origin food products (meat, milk egg, fish) over the last 15 years for the same countries as studied in figure 2. The consumption is expressed as percentage of the total calories consumed. It shows that in the developing countries meat consumption is low (5-10%) with rising GDP values the consumption increases fast to 35% of the calories. At GDP values of about 10.000 \$ per capita, a saturation level is reached and meat consumption levels remain at this 35%. In the high income countries like USA and Western Europe consumption of animal products actually did not increase over the last 15 years. The largest changes in meat consumption occur in the fast growing economies in Asia (India and China). These countries have GDP values above 2,000 per person, and due to the fast economic growth, their GDP is increasing fast. Figure 4 shows that meat consumption per person in China doubled over the recent 15 years. Poleman and Thomas (1995) showed that the relation between GDP and the consumption of animal products holds for many more countries than those in the sample presented here.

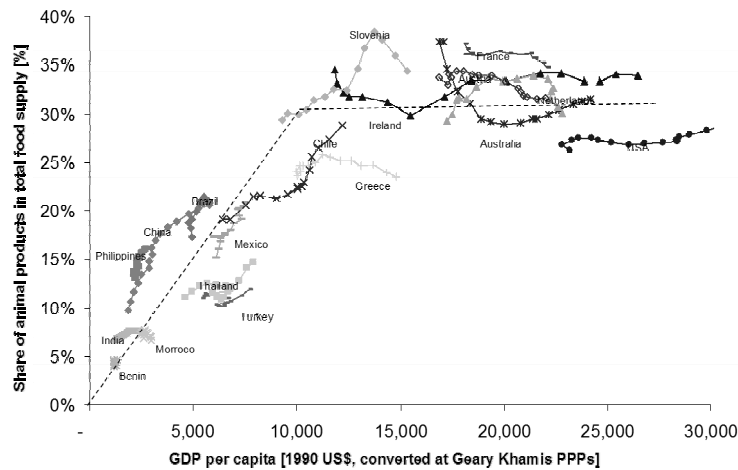


Figure 4. The relative consumption of animal origin food products (share in total calories consumed) in relation to GDP per capita. The dotted line shows the relation between GDP and consumption of animal products used in this paper. (Data are for the years 1990 – 2005; sources FAOSTAT, 2007; GGDC, 2007).

3. ENERGY DEMAND

Figure 5 shows the development of global energy use since the mid-19th century, both the total consumption as the main energy sources are shown. Until 1900 the consumption was more or less constant at 20 EJ y⁻¹. After the industrial revolution the total energy use increased to nearly 500 EJ y⁻¹. Besides this enormous increase in total consumption also a change in energy sources is evident. Before the industrial revolution energy consumption was mainly supplied by wood and in present days it is a mix of several energy sources.

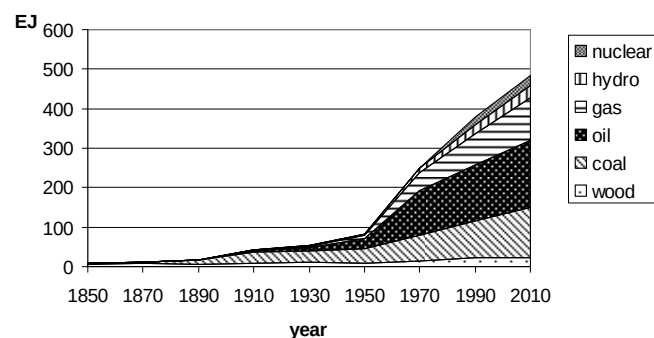


Figure 5. Development of global primary energy use according to main energy sources 1850 – 2010; (adapted from Grubler and Nakicenova, 1997, using data from IEA 2009a).

Presently coal, oil and gas are account for over 90% of the energy use (figure 5). These energy carriers are fossil, they originate from plant material produced in ancient times and combustion of these energy sources lead to emissions of CO₂.

In figure 6 we show the energy use per capita for the same group of countries as in figures 2 and 4. With respect to energy use a more or less linear relation is found between GDP and energy use. The rich countries are requiring nearly 5 times as much energy as the poor countries. But also large differences between countries at the same level of welfare exists. A person in the USA is using 350 GJ/year, while a person in Ireland, at the same welfare level only needs 200 GJ/year.

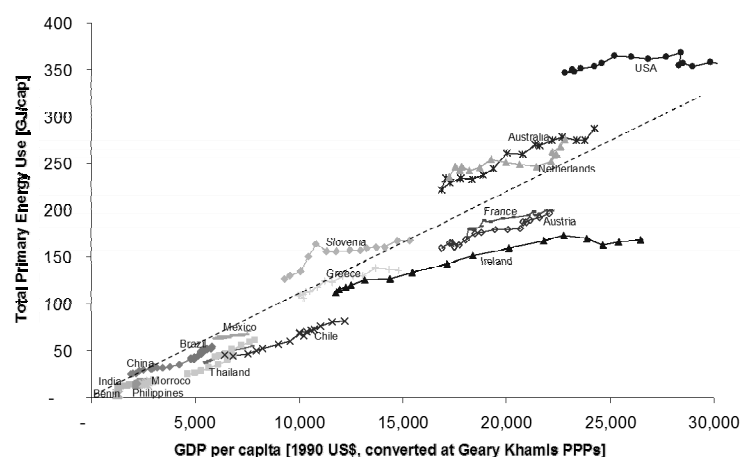


Figure 6. Energy use per capita as function of GDP. Dotted line shows relation used in this paper. (Data are for the years 1990 – 2005; sources EIA, 2007, GGCD,2007).

4. ASSESSING FUTURE FOOD, FEED AND FUEL NEED IN VARIOUS PARTS OF THE WORLD

In the previous paragraphs we described past and present needs for food, feed and fuel in various parts of the world. When talking about future needs, one has to realize that the drivers behind changing demands differ between countries. In some countries population growth is large, in some countries there is a strong increase in the demand for meat and in other countries new energy policies are put into practice. We simplify the large variety in welfare throughout the world into three groups: poor people living in developing countries, rich people in Western Europe (EU) and the USA, and people in the so-called transition countries showing a fast economic development.

In developing countries (GDP up to \$ 2000 per capita) consumption of meat and energy is very low, but population growth is large (around 2%). This implies that in the coming decades these countries need extra food to fulfill the needs of their growing populations. At present these countries accommodate around 3 billion people (Worldbank, 2008). Assuming population growth at 2%, this population will increase to 5 billion within 20 years. Since, in these countries, economic development is slow, neither major changes in meat consumption nor an increase in the use of biomass as an energy source are expected.

About 2 billion people are living in the so-called transition countries; these countries show fast economic development with GDP growth rates of around 6% per year. This implies that within 20 years their GDP will grow from around \$ 2.000 to 10.000 per capita. Following the relation shown in figure 4, their animal product consumption will reach saturation levels of around 35% of total calories consumed. This implies that for these countries the needs for livestock feed will increase.

The EU and the US together have about 1 billion inhabitants. In these countries population increase is low and their animal product consumption has reached the saturation levels. Therefore no drastic changes with respect to biomass needs for food and feed are to be expected. However, these countries are putting energy policies aimed at combating the effects of climate change into place. Biomass, often considered a carbon neutral energy source in this context, is playing an important role in these policies. Most policy plans mention a target of 10% of total energy supply from biomass for 2020/2030 (Steinbeck, 2007; OECD-FAO, 2009). Present energy use in developed countries is at 200 to 400 GJ per person per year. The policy goals therefore imply that at least 20 GJ of energy should be obtained from biomass within 20 years.

5. QUANTIFYING BIOMASS NEEDS FOR FOOD, FEED AND FUEL PER CAPITA

Since it is not possible to compare kilograms of rice, liters of milk, kWhs of electricity and liters of gasoline, for our study all biomass demands should be converted into one common unit. In here we use the methodology developed in Nonhebel & Kastner 2010. We assume that a simple diet in developing countries mainly based on staples requires 400 kg of wheat per person per year (based on Luijten, 1995). The affluent diets in the OECD countries contain 100 kg of meat. Since 4 kg of wheat is required to produce 1 kg of meat (Nonhebel, 2007), the affluent diets require 400 kg of wheat as livestock feed. The total need for food and feed for affluent diets is therefore 800 kg per person. There are different routes to convert biomass into energy: it can be combusted in a power plant yielding electricity, grains can be fermented providing ethanol that can be used as a transport fuel, but biomass can also be used in a digester, producing methane (gas). Using biomass as a feedstock for electricity generation provides the largest CO₂ savings; in that case biomass is replacing gas, or coal (Wahlund et al, 2004). The heating value of dry biomass is 18 MJ/kg. This factor can be used to convert energy, expressed in Joule, into biomass needs (grains). For our example, the production of 20 GJ of energy requires about 1100 kg of biomass.

6. COMPARISON OF BIOMASS NEEDS FOR FOOD, FEED AND FUEL ON A GLOBAL SCALE

We now use this basic categorization and assumptions to assess (additional) global biomass needs in the near future. Figure 7 shows the overall results in 4 different graphs: the upper two show the results per person (kg/capita) and the lower two show the results in absolute terms (MT). The 1 billion people in the developed part of the world require 400 kg cereals for food and 400 kg for feed (A). The other 5 billion people (3 billion in developing countries and 2 billion in the transition countries) have very simple menus, containing only very small amounts of affluent products. They require only 400 kg of cereals per person. At the global scale, this results in a total need for cereals of about 2800 MT per year. The largest share, 2400 MT, is for food, 400 MT is needed for livestock feed, for meat consumption in the developed countries. Note that a person in the EU/USA requires twice as much grain as a person in Africa. The total need for food is largest in developing countries (1200 MT) due to the number of people living there (C). The total cereal demand in transition countries (2 billion people) is as large as the demand in developed countries (1 billion people).

Assuming changes in biomass demand as discussed in the sections 4 and 5, the following picture emerges: consumption patterns in the developing countries remain at the same basic levels; therefore still 400 kg of cereals are needed per person. In transition countries higher shares of animal products enter the diet, implying an additional need for livestock feed of 400 kg per capita. In developed countries, menus do not change, but biomass is needed as a result of changes in the energy supply system. As a consequence, in these countries the need for biomass for fuel is considerably larger than the combined need for food and feed (B).

At the global scale, (D) the large population increase in the less developed countries leads to an additional need for food of 800 MT, while the cereal needs for food in the other parts of the world remain the same. The need for livestock feed in the transition countries leads to a cereal demand of 800 MT, equaling the additional need for food in developing countries. Finally a large cereal demand as energy carrier (1100 MT) in developed countries emerges.

The overall result of this basic model calculation is that within 20 years the global demand for cereals will almost double from 2800 to 5500 MT.

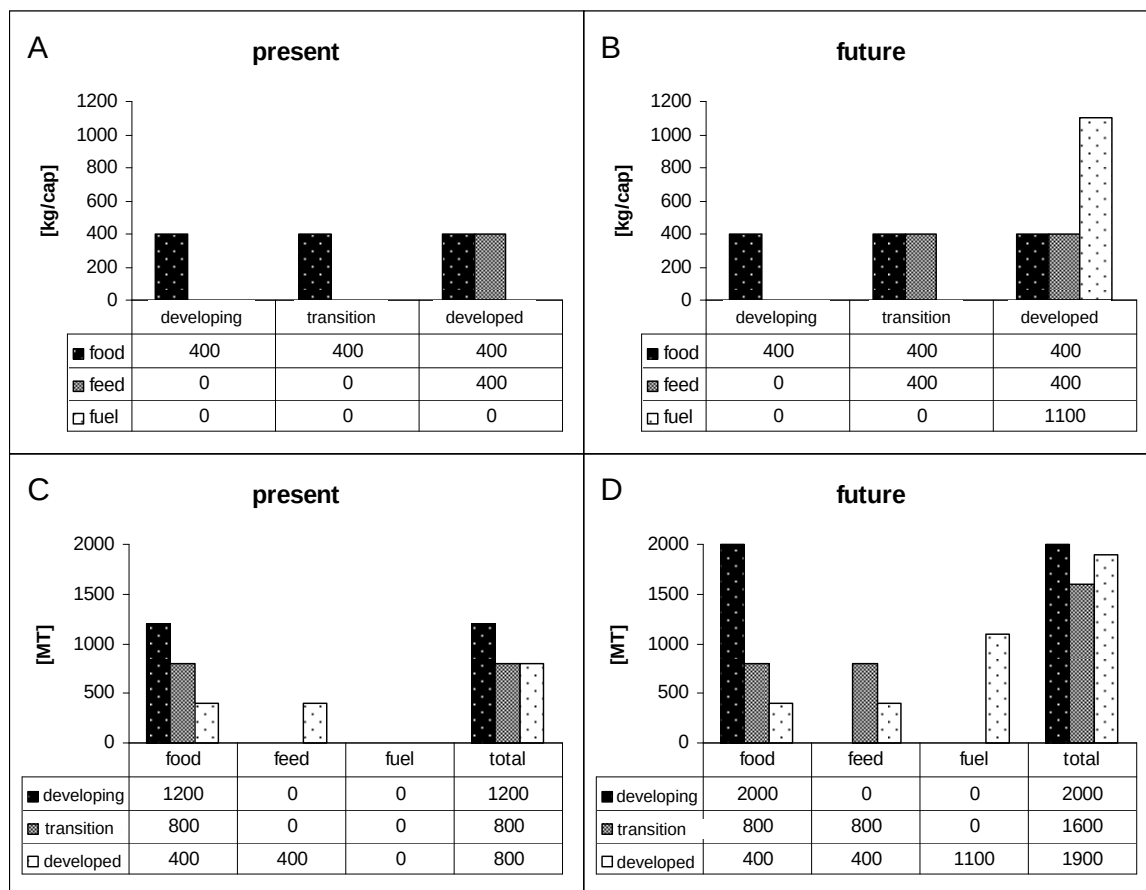


Figure 7. Demands for food, feed and fuel as calculated with the model presented in this paper. (A) Present per capita demand, (B) near future per capita demand (2 decades), (C) present needs on a global scale, and (D) near future needs on a global scale

7. DISCUSSION AND CONCLUSION

The model presented in this paper involves large simplifications. It only considers two different diets and one type of renewable energy in three different economies. The actual situation shows much more variation around the globe and for forecasting future needs for food, feeds and fuel more detailed models will be required. The goal of this analysis, though, is to determine the order of magnitude of the need for biomass as an energy source within the next decades in comparison with the needs for food and livestock feed. Therefore we only discuss the results of the model according to their order of magnitude.

The present need for food and feed at a global scale is calculated to be 2800 MT cereals per year (figure 7). The present global production of cereals is 2100 MT, which is far lower than the model output. However, the model assumes that all needs are fulfilled with cereals, while in practice cereals only supply 70% of the calories consumed on global scale (the remainder is fulfilled with potatoes, beans etc. (FAOSTAT, 2007)). Moreover it is assumed that meat is obtained from livestock fed with cereals, while in practice a large share of the animal products originates from ruminants fed with roughage. Correcting for this, the model outcomes reflect the actual situation quite well.

With respect to the future needs the model outcomes show an increase of cereal demand by 1600 MT (50%) for food and feed within 20 years; this is in accordance with FAO estimates. The OECD-FAO (2009) report on biofuels and food claims that half of the extra needs for cereals in the near future will be due to the use of biomass for energy purposes. In our model this value is 30%; this difference can be again explained by the

fact that we assume that all food is provided by cereals, and therefore the fraction needed for energy purposes will be smaller.

With respect to the need for food, feed and fuel within the next decades, the results of our basic model show the same pattern as those provided by more complex models used by FAO and OECD. This implies that the values presented are in accordance with the estimates available in this research field. We can now focus on the consequences of our findings for the food supply system.

First it is striking that the need for biomass for energy is huge in comparison with the need for food and feed. The policy goal of obtaining only 10% of the energy needs from biomass is going to more than double the biomass needs in developed countries. Presently 400 kg is needed for food, 400 kg is needed for livestock feed, and the need for energy will be at 1100 kg per person per year (figure 7). According to these values, the need for energy will be nearly three times as large as the need for livestock feed. Therefore a person in the developed world, with a luxurious diet and obtaining 10 % of his/her energy from biomass requires four times more biomass resources as a person in a developing country on a simple diet and without access to comparable energy sources. The value is still more than twice the amount of biomass per person used in the transition countries. This large difference results from the high energy use levels in the developed part of the world: figure 6 shows that they are above 200 GJ per person per year. The average food consumption per person equals only about 10 MJ per day (2500 kcal): on annual basis this is 3.6 GJ. When 10 % of the total energy demand is to be fulfilled with biomass, 20 GJ is needed: this is five times the need for food. This huge difference also indicates the limited potential of rest streams from the food system as energy source. Since the demand from the energy system is 5 times as large as from the food system it is obvious that residues from the food system will never be enough to full fill the energy needs, which implies that extra crops have to be grown.

7.1 Consequences of findings for global cereal markets and food security

Figure 8 shows the cereal production in various continents and the imports and exports. The production is highest in Asia and lowest in Africa, due to the differences in population. It is remarkable that continents are producing more or less enough food for their own population.

Only a small fraction (285 MT (10%)) of the total production is actually sold on the world markets. North America and Europe are exporting, while Africa and Asia are importing.

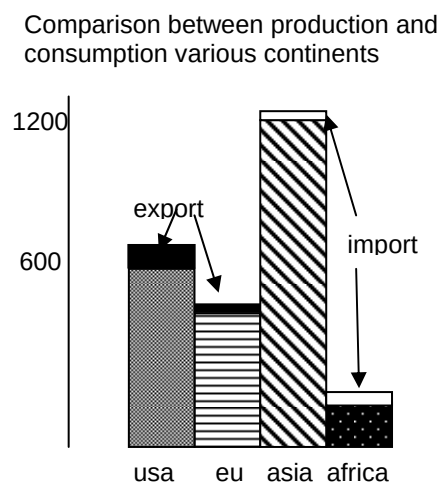


Figure 8. Comparison between cereal production and consumption, imports and exports in MT for 4 continents (source FAOSTAT), see text for explanation.

The fact that local markets are far larger than the global market, makes it interesting to analyze the consequences of the future needs per continent.

The present production of Asia and Africa is 1250 MT and they import 100 MT from the global market. In the coming decades their needs for food increase from the present 1350 to 2050 MT (50%), due to increase of population and changing consumption patterns. In the last 20 years production in Africa increased with over 70%, in Asia the increase was smaller: 40%. Based on the achievements in history the increase in production of 50% in the coming decades seems possible.

Another picture emerges when we study Europe and the US. Presently they are net exporters they produce more food (1050) than they can consume (950) and export 100 MT. Their production have to double in 20 years to meet the needs for energy (1100). However, in the last 20 years the cereal production in these continents increased with only 10 %, so in these continents major system changes are needed to meet the increased requirements. Climate policy plans recognize this problem and mention that extra imports are needed to achieve the biomass for energy goals. This may mean that OECD countries change from net exporters into net importers.

However, presently the exports from both EU as USA play vital roles in food security in many low income countries. 75-80% of grains available on the world market is imported by developing countries and used for food and feed. The situation in Africa is worst: this continent is actually importing 30% of its demand for wheat and maize. For individual countries even larger values are found: Egypt is importing 50% of its demand (OECD/FAO, 2009). When the EU and USA reduce their exports this may lead to shortages on global markets, increasing costs for food and food security problems in third world countries. Moreover the need for biomass for fuel in the OECD countries (1100 MT) is 4 times larger than the total volume available on the world markets (285 MT). When present energy plans are really put into practice by implementing regulations and incentives (subsidies, etc.), the cereal demand will be far larger than is available at present. Resulting in serious disturbances on global food markets. This implies that the present energy policies in the OECD countries carry the risk of generating food insecurity in low income countries.

REFERENCES

- Evans L.T., 2001. *Feeding the ten Billion*, Cambridge university press, Cambridge, . 247pp.
- FAOSTAT, 2007. *FAOSTAT Statistical Database*. (<http://faostat.fao.org/>)
- FAO 2009. *The state of Agricultural commodity markets 2009*. FAO, Rome, 63 pp.
- FAO, 2008. *The state of food and agriculture 2008, biofuels, prospects, risks and opportunities*.
- GGDC 2007. *The Conference Board and Groningen Growth and Development Centre*, Total Economy Database, November 2007. (<http://www.conference-board.org/economics>)
- Grubler, A and Nakicenovic, N., 1997 "Decarbonizing the global energy system" *Technological Forecasting and Social Change* 53, 97-110
- IEA 2009a, *Annual Energy Review 2008* Report No. DOE/EIA-0384(2008)
- IEA, 2009b. *Key World Energy Statistics*, IEA, Paris, France.
- Luijten, J.C., 1995. *Sustainable World Food Production and Environment*. AB-DLO Report no. 37. ABDLO, Wageningen, The Netherlands.
- Nonhebel, S., 2007. "Energy from agricultural residues and consequences for land requirements for food production". *Agricultural Systems* 94, 586-592.
- Nonhebel, S., Kastner T., 2010. "Changing demand for food, livestock feed and biofuels in the past and the near future". *Livestock Science* accepted.
- OECD-FAO, 2008. *Agricultural-outlook 2009-2018*, OECD, Paris, France, 279 pp
- Poleman, T.T. and Thomas, L.T., 1995. "Income and dietary change", *Food Policy* 20 (2) 149-159.
- Steinbeck, R., 2007. *Biofuels at what cost?* International Institute for Sustainable development, Geneve, Switzerland. 72 pp.
- Trostle R., 2008. *Global Agricultural supply and demand: factors contributing to the recent increase in food commodity prices*, Economic research service/ USDA. WRS-0801.
- World Bank, 2008. *World Development indicators 2008*, Worldbank, New York, USA

United States Department of Agriculture (USDA) Foreign Agricultural Service (FAS). 2007. *Production, Supply & Distribution Online Database*. USDA: Washington, D.C. Available online at <http://www.fas.usda.gov/psdonline/>.

WIND POWER IN CHINA: DREAM OR REALITY

Xin Li^{1*}, Klaus Hubacek^{1,2}, Yim Ling Siu^{1,3}

¹ *Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK.*

² *Department of Geography, University of Maryland, College Park, MD 20742, USA.*

³ *State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, PR China.*

ABSTRACT

With cumulative generating capacity doubling over the last five years, China now has 26 GW of wind-derived power and is second only to the US. In 2009, one third of all new wind turbines globally were installed in China. Despite the recent growth rates and promises of a bright future, two important issues - the capability of the grid infrastructure and the availability of backup systems - must be critically discussed and tackled in the medium term. The analysis shows that only a relatively small share of investment goes towards improving and extending the electricity infrastructure which is a precondition for transmission of produced clean wind energy to the end users. In addition, the backup systems are either geographically too remote from the potential wind power sites or currently financially infeasible. Finally, the introduction of wind power into coal-dominated energy production system is not problem-free. The frequent ramp ups and downs of coal-fired plants induce lower energy efficiency and higher emissions, which is likely to cancel out the emission saving from wind power. The current system is heavily reliant on independently acting but state-owned energy companies optimizing their part of the system, which is partly incompatible with building a robust power system supporting renewable energy technologies. Hence, strategic, top-down co-ordination and incentives to improve the overall electricity infrastructure must be achieved.

Keywords: wind power, power grid, back-up system, China

1. INTRODUCTION

China's wind energy industry has experienced a rapid growth since the early 2000s. The cumulative installed capacity of wind energy has doubled for five consecutive years and amounted to 26 GW by the end of 2009 (GWEC, 2010). The newly installed capacity in 2009 reached 13 GW which accounted for one third of new windmills globally. The wind energy potential in China is enormous. According to He et al. (2008), the exploitable wind energy potential is 600 – 1,000 GW onshore and 100 – 200 GW offshore. McElroy et al. (2009) predicted that wind energy could generate 6.96 trillion kWh of electricity by 2030, which is sufficient to satisfy China's electricity demand in 2030. Despite the recent growth rates and promises of a bright future, two major issues must critically be discussed and clarified in light of the Chinese wind energy diffusion process: 1) the capability of the grid infrastructure to absorb and transmit the huge amount of wind powered electricity, especially when these wind farms are built in remote areas; 2) the choices and viability of the backup systems to cope with the fluctuations of wind electricity output.

* Corresponding author; E-mail: k.hubacek@leeds.ac.uk; Telephone: +44(0)1133431631

2. IS THE POWER GRID INFRASTRUCTURE SUFFICIENT?

Wind power has to be generated at specific locations with sufficient wind speed and other favourable conditions. In China, most of the wind energy potentials are located in remote areas with sparse population and less developed economies. It means that with less wind powered electricity consumed at the source, a large amount of electricity has to be transmitted between supply and demand centres leading to two important problems associated with the integration into the national power grid system: investment and grid safety.

2.1 Power grid investment

Although the two state grid companies - the State Grid Corporation of China (SGCC) and China Southern Grid (CSG) - have invested heavily in grid construction, China's power grid is still insufficient to cope with increasing demand. This situation is a result of an imbalanced investment between power grid construction and power generation capacity. For example, during the periods of the Eighth Five-Year Plan, Ninth Five-Year Plan and Tenth Five Year Plan¹, power grid investments accounted for 13.7%, 37.3% and 30% of total investment in the electricity sector, respectively. Although the situation has improved as the ratio increased from 31.1% in 2005 to 45.94% in 2008, the cumulative investment in the power grid is still significantly lower than the investments in power generation (State Electricity Regulatory Commission, 2009). Figure 1 gives a comparison of the ratios of accumulative investments in power grid and power generation in China, the US, Japan, the UK and France since 1978. In most of these countries, more than half of electric power investment has been made on grid construction. By contrast, the ratio is less than 40% in China.

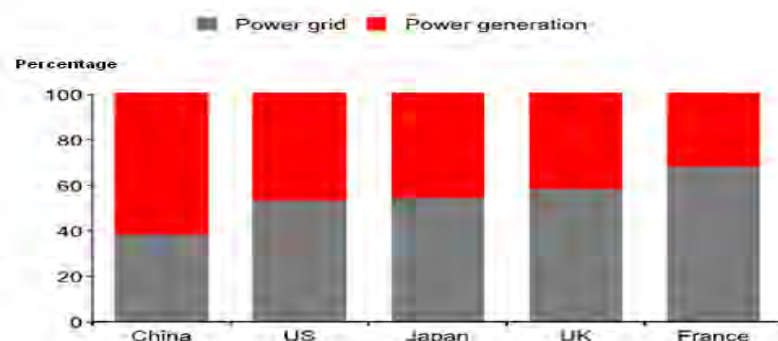


Figure 1. Ratio of accumulated investment in power grid and power generation since 1978.

Source: (Fenby and Qu, 2008)

The integration and transmission of wind power require significant amounts of capital investment. The Three Gorges power plant has provided an example of large-scale and long-distance electricity transmission in China. Similar to wind power, hydropower is usually situated in less developed areas. As a result, electricity transmission lines are necessary to deliver the electricity to the demand centre where majority of them are located in the eastern coastal areas and southern part of China. According to SGCC (2007), the grid reinforcement investment of the Three Gorges power plants amounted to 34.4 billion Yuan (about 5 billion US dollars). This could be a lot higher in the case of wind power due to the following reasons: first, the total generation capacity of Three Gorges project is approximately 17 GW compared to the planned generation capacity of over 100

¹ The Five-Year Plan - is the strategic planning of five consecutive years of the economic development in China. For example, the Eighth Five-Year Plan is from 1991 to 1995, the Ninth Five-Year Plan is from 1996 to 2000 and the Tenth Five -Year Plan is from 2001 to 2005, and so forth.

GW in the proposed wind farm locations. Hence, more transmission capacities are required. Second, the Three Gorges hydro-power plant is located in central China. A number of transmission paths are available, such as the 500 kV DC transmission lines to Shanghai (with a length of 1,100 km), Guangzhou (located in Guangdong province, length of 1,000 km) and Changzhou (located in Jiangsu province, length of 1,000 km) with a transmission capacity of 3 GW each and the 500 kV AC transmission lines to Central China with transmission capacity of 12 GW. By contrast, the wind farm bases are far away from the load centres with the exception of the Eastern Inner Mongolia. For example, Jiuquan located in Gansu has a planned generation capacity of 20 GW. The distances from Jiuquan to the load centre of Central China grid and Eastern China grid are 1,500 km and 2,500 km, respectively. For Xinjiang, the distances are even longer at 2,500 km and 4,000 km, respectively. As a result, longer transmission lines are required. Figure 2 depicts the demand centres and wind farms in detail.

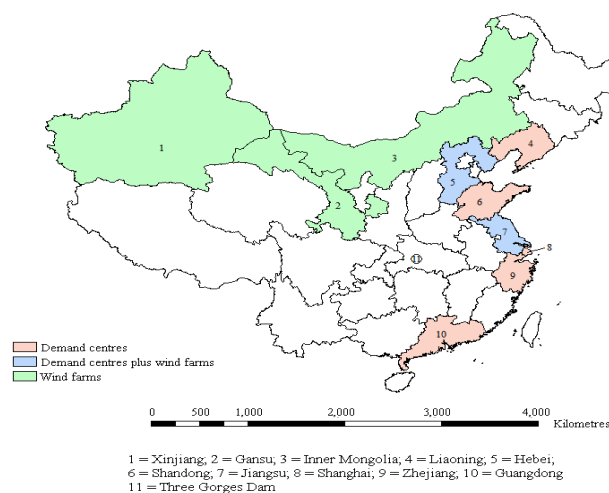


Figure 2. Locations of wind farms and demand centres. Source: Figures for wind farms from (Xinhua, 2009); Figures for demand centres from (Electric Power Yearbook, 2009)

2.2 Grid Safety

The second problem is related to grid safety. To the power grid operator, wind powered electricity is less favourable due to its fluctuating electricity output (Li, 2010). The large scale penetration of wind electricity leads to voltage instability, flickers and voltage asymmetry which are likely to cause severe damage to the stability of the power grid (Chen and Blaabjerg, 2009). It is believed that the smart grid could provide a solution to the large-scale production of wind energy in the future, but the investment in smart grid and related regulations are uncertain (Wang and Nakata, 2009). In addition, the UHV transmission lines (1,000 kV and 800 kV) reduce the electricity loss and increase the transmission distance significantly compared to the 500 kV lines (Zhang et al., 2007). However, the UHV projects are still under experimentation, further investment might be made when the demonstration projects are successful (SGCC, 2007).

Although the Chinese Renewable Energy Law requires the power grid operators to coordinate the integration of wind mills and accept all of the wind powered electricity, due to the above mentioned problems, the power grid companies have been reluctant to do so. For instance, more than one third of the wind turbines in China, namely 4 GW, were not connected to the power grid by the end of 2008 (SERC, 2009). Given that the national grid in China is exclusively controlled by SGCC and CSG, the willingness of these two companies to integrate wind energy into the electricity generation systems is critical.

3. ARE THE BACKUP SYSTEMS GEOGRAPHICALLY AND TECHNICALLY FEASIBLE?

The variability of electricity output from wind power results in difficulties in the integration of wind power into the regional and national power generation systems (Drake and Hubacek, 2007). A number of attempts have been made to justify the approaches to stabilize the electricity output from wind power plants. In China, He et al. (2008) investigated the choices of combined power generation systems. The combinations of wind-hydro, wind-diesel, wind-solar and wind-gas power were evaluated respectively. They found that the wind-diesel and wind-solar hybrid systems have been used at remote areas due to lower generation efficiency and higher generation costs compared to other generation systems. Hence, the next section looks into the application of wind-hydro, wind-gas hybrid systems and energy storage systems in detail and evaluates the existing coal based backup systems in China.

3.1 Wind-hydro combined electricity generation system

China has one of the largest hydropower resources in the world and its total exploitable capacity amounts to 542 GW (Li and Shi, 2006). As one of the major sources in the electricity mix, hydropower has contributed to approximately 15% of the total electricity consumption in China (Electric Power Yearbook, 2009). However, the choice of the wind-hydro power generation system is dependent on the locations of the available energy sources. Figure 3 depicts the wind farm locations and hydropower potentials in China.

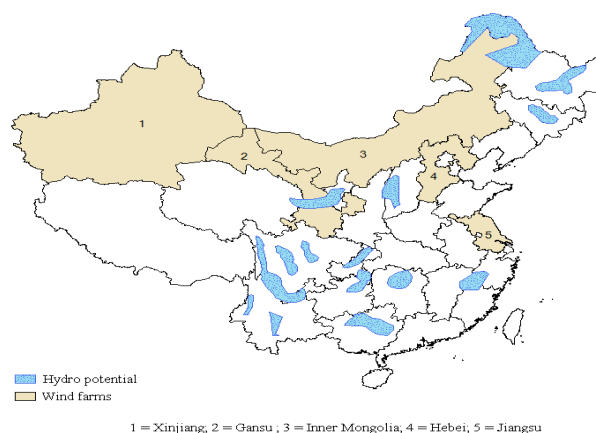


Figure 3. The distribution of hydropower potential and the locations of wind farms in China
Source: Figures for hydropower potential from (Wang and Chen, 2010); Figures for wind farm locations from (Xinhua, 2009)

Given that most of the hydropower resources are located in central China, He et al. (2008) suggested that wind-hydropower generation system might not be appropriate in specific areas such as Inner Mongolia, Hebei and Jiangsu, as the spatial distributions between the wind energy potentials and the hydropower potentials are not consistent.

3.2 Wind-gas combined electricity generation system

The other solution to balance the power outputs from wind power is the application of wind and natural gas combined generation system. Compared to other thermal power generation systems, the natural gas power generation system has the advantages of less pollution, higher efficiency and quicker response. The China Academy of Engineering

(CAE) has carried out a feasibility study of the combined power generation system in Xinjiang. In this analysis, a number of factors were examined such as the generation capacity of the wind farm, capacity factor of the wind turbine and the generation capacity of the natural gas power plant. The CAE study concluded that with capital cost at 7,500 Yuan/kW for wind farms, natural gas price at 1.2 Yuan/m³ and wind turbine capacity factors at 30%, the cost of wind-gas combined power generation system is 0.5 Yuan/kWh. Although the cost of hybrid generation system per unit of electricity output is higher than the cost of wind powered output alone (0.42 Yuan/kWh), it is economically viable if the stability of power grid is taken into consideration (He et al., 2008).

However, these findings might be misleading due to a number of reasons. First, the capital costs of wind farms are higher than 7,500 Yuan/kW. According to Liu and Yang (Liu and Yang, 2008), the capital investments of wind mills are approximately 10,000 Yuan/kW for MW-level wind turbines in 2008. Second, the end-user prices of natural gas vary significantly amongst regions due to the lengths of transportation from the supply centres to the demand centres. The price for industrial use gas is in Inner Mongolia, Gansu, Xinjiang, Hebei and Jiangsu are 1.67 Yuan/m³, 1.25 Yuan/m³, 1.25 Yuan/m³, 2.00 Yuan/m³ and 2.75 Yuan/m³, respectively (Higashi, 2009). Third, China had been self-sufficient in natural gas supply up until 2006. The increasing demand and limited domestic supply have resulted in gas imports in recent years. Although several agreements have been made between China and Russia, Turkmenistan and other supply countries to guarantee natural gas supply, the prices of imported natural gas are twice as much as from domestic supply. Since increasing amounts of natural gas has to be imported, the current natural gas price regime is likely to change. Hence, power generation companies have been reluctant to use natural gas as a major electricity supply source. By the end of 2006, gas-fired power plants accounted for only 2.5% of total generation capacity (Higashi, 2009). Fourth, the capacity factors of wind farms in China are far below the expected level. The State Electricity Regulatory Commission (SERC, 2009) found that six out of seven wind farms, which were randomly selected in seven provinces, had less operating hours (1,864 hours on average) than the designed operating hours (2,305 hours on average). The capacity factors of these six wind farms are 21.3% which is considerably below the expected 26.3%. Last but not least, there is no doubt that the hybrid generation system would help to reduce the variation of the electricity output from wind farms. However, the total electricity output from the hybrid generation system might double the electricity output from wind farms alone. For example, in the CAE study, the total electricity generation amounts to 1.3 billion kWh from the hybrid system per year, with 0.52 billion kWh from the wind farm and 0.78 billion kWh from the natural gas power plant (He et al., 2008). Considering most of the electricity needs to be transmitted to the demand centres, which are around 3,000 km away, it will require more lines and capacities in electricity transmission. As a result, none of the assumptions, which have been made in the CAE study to justify the economics of wind-gas generation systems, have been met. The wind-natural gas hybrid system remains doubtful in the future.

3.3 Energy storage systems

As mentioned above, the integration of large-scale wind farms to the insufficient grid infrastructure might result in instability of the power grid. In addition, the feasibility of hybrid power generation systems remains doubtful due to geographical and economic reasons. Another option in wind energy integration is the application of an energy storage system.

There are two types of energy storage systems available at present. First, physical energy storage systems such as wind powered pumped hydro storage system (Bueno and Carta, 2006) and compressed-air system (Enis et al., 2003) are used. However, the applications of the physical energy storage systems are constrained by geographic conditions and capital costs. For instance, wind powered pumped hydro storage system requires large areas and sufficient water resources for the upper and lower reservoirs. By

the end of 2007, there have been 18 pumped hydro storage plants operated in China. Another 11 plants are under construction. However, only one pumped hydro storage plant was built in the most important three wind farm base locations (Inner Mongolia, Gansu and Xinjiang) (China Pumped Storage Plant Network, 2010). In addition, a number of electrochemical energy storage systems are available, such as lead-acid battery energy storage systems, redox flow cell energy storage systems and sodium-sulphur battery energy storage system. Compared to the physical energy storage systems, the maximum energy storage capacity could only reach 10 MW (He et al., 2008). Since the majority of the wind farms have a generation capacity of 50 MW, the electrochemical batteries are not appropriate to be used as energy storage systems in China. Consequently, hybrid generation systems and energy storage systems are likely to solve the wind-powered electricity fluctuations in some areas. However, such systems will only serve a limited proportion of proposed wind farms in the future. The majority of the wind generation capacities still require considerable efforts for the integration into the regional or national power grid systems.

3.4 The available choices for backup systems under current conditions

With thermal power serving more than 90% of the electricity demand, the choices of using coal-fired plants as backup system in provinces such as Inner Mongolia, Hebei and Jiangsu are inevitable. The choice of using coal-fired power plants as backup system raises a number of questions; namely, what is the efficiency loss of using coal-fired plants to backup wind power; to what extent do coal-fired backup systems cancel out the 'emission savings' from wind energy; is it economically viable to construct coal-fired plants in remote areas and transmit the electricity to the demand centres?

To answer these questions, a brief introduction of the electricity systems' operation is needed. In electric power systems, the system operator usually schedules the hourly electricity supply the day before dispatch. However, the forecasting inaccuracies are to some extent inevitable because of the contingencies such as the time-varying (intra-hour) demand and unscheduled blackouts of power plants. The scheduled supply, also known as base load, is provided with lowest marginal costs units such as coal-fired plants and nuclear power plants. The discrepancies between the scheduled supply and the actual demand are met with balancing reserve units, such as natural gas-fired plants and hydropower plants, which could balance the supply and demand with quick responses to the electricity output. Compared with other energy sources, coal power plants provide the cheapest electricity as the externalities of burning coal are not taken into account. However, the coal-fired plants are difficult to operate when a quick response to changing electricity demand is needed as it results in lower energy efficiency (White, 2004).

As stated by Goggin (2008), the integration of wind power to the power grid is likely to result in a decrease of energy efficiency for thermal power plants. The loss of energy efficiency comes from the frequent start-up and shut-down of these plants in order to balance the fluctuating electricity output of windmills. However, the frequent adjustment of power output of coal-fired plants results in much higher CO₂ emissions per kWh power output than in normal operation mode. For example, White (White, 2004) concluded that a 2% energy efficiency loss would result in a 150 grams CO₂ emission growth per kWh electricity output for a coal-fired boiler. The figure for a greener power generation system – the combined cycle gas turbine plant – is still 30-50 grams per kWh power output. Consequently, the loss of energy efficiency might have significant impacts on the overall CO₂ emission from conventional power plants. In addition, the design and operation of these base load providers fit a stable and continuous power output mode. The ramping ups and downs might cause more frequent and higher costs of maintenance (White, 2004). Another issue of using coal as a backup is the same as previous mentioned challenges in section 3.2 – the total power output from the combined system might be significant. To sum up, the use of coal-fired plants as the backup system is unavoidable because of the coal-dominated electricity mix.

4. POLICY IMPLICATIONS

4.1 A systems approach to energy planning

With the six proposed wind farm locations, GWEC (2010) predicted that more than 150 GW of wind turbines are going to be deployed by 2020. Still, the lack of an integrated approach towards optimizing the whole energy system might make this a futile effort.

The current Chinese policies focus on installed capacity in the pursuit of a sustainable electricity mix. For instance, the Medium-Long Term Renewable Energy Development Plan has stipulated the responsibility of power generation companies which have more than 5,000 MW generation capacities to contribute 3% and 8% of their generation capacity to non-hydro renewable energy sources by 2010 and 2020, respectively. The mandatory timelines and proportion commitments have induced the large power generation companies to increase capacity growth contributing to the actual operating hours of wind turbines being much lower than the expected operating hours. According to Liu and Yang (Liu and Yang, 2008), more than 70% of the windmills were owned by these large power generation companies by the end of 2007. Installing large numbers of wind turbines alone, although creating workplaces in several industrial sectors such as manufacturing, transportation and finance is not a sufficient reason by itself unless when they are being used for electricity generation. Thus, the tremendous growth in generation capacity is exciting but not convincing. As a result, large efforts are urgently needed towards the optimization of the entire power generation system rather than focusing on an individual component.

4.2 Coal as backup: one step forward two steps back

A number of studies have examined the impact of large-scale wind energy on the power generation systems in various countries, such as Denmark, Germany and the US (Holtinen, 2009). It is noticeable that these countries have either significant proportions of flexible power generation units or well-connected power grid or both. With limited power grid infrastructure, it remains worrisome when large-scale wind energy is integrated into the coal-dominated generation system in China. The Chinese government should notice that capacity displacement is a necessary but not a sufficient condition in the measurement of CO₂ emission reduction in the power system. In other words, the displacement of traditional thermal power plants with more sustainable energy sources is necessary to reduce the overall CO₂ emissions in the power system; however, the loss of energy efficiency in coal-fired plants due to smoothen out the wind powered output will result in higher CO₂ emissions, which might cancel out the emission savings of wind energy. Consequently, the current coal-dominance of the Chinese power system creates a serious problem to the development of wind energy.

4.3 Strategic planning of the power grid at regional and local levels

Grid connection and grid reinforcement are critical to the development of wind energy in China. The existing transmission lines are rapidly approaching their limits. In addition, new transmission lines are required as the installation of new wind turbines are increasing. The planning of new transmission capacity is a long-term and strategic task. First, the deployment of windmills takes years to complete. Second, wind electricity costs at source are already higher than conventional power sources; higher added cost could damage the willingness to accept wind electricity. Another issue to note is that the SGCC, which owns the majority of the electricity transmission and distribution assets, has invested in wind farms. Because of the monopoly in the power grid operation by SGCC and CSG, the participation of power grid owners in wind energy development might induce an unfair competition, such as giving priorities to their own wind farms during integration and electricity purchase. Consequently, a policy focusing on the responsibility

of the grid company, such as whether the power distribution and transmission companies should invest in power generation assets, is critical and necessary. Such policy should also emphasize the construction of smart grid and UHV transmission lines, which are necessary to the large-scale integration of wind energy into the existing electricity mix.

In addition, a coordinated power grid network might help to reduce the variability of wind power output. It is believed that the dispersed wind farms (up to thousands of kilometres) would take advantages of the different weather conditions in various locations and decrease the variability of the power output as a whole. As the wind farms are geographically dispersed in China, the combination of wind farms might be able to cope with the power output fluctuations. But again, this is not feasible in the current context given the disparate networks and lack of infrastructure investment in China. The shortage of investment in grid has been changing gradually, especially at the latter period of the 11th Five Year Plan. Nevertheless, sustained efforts need to be made to accommodate wind energy in the coming decade because the overall power generation system is only as strong as its weakest link. Hence, emphasising the whole system and focusing on the bottlenecks are the foundations of building a robust and sophisticated electric system.

REFERENCES

- Bueno, C. & Carta, J. A. 2006. "Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands". *Renewable and Sustainable Energy Reviews*, 10, 312-340.
- Chen, Z. & Blaabjerg, F. 2009. "Wind farm--A power source in future power systems". *Renewable and Sustainable Energy Reviews*, 13, 1288-1300.
- China Pumped Storage Plant Network. 2010. *Existing, under construction and proposed projects* [Online]. [In Chinese]. Beijing. Available: http://www.psp.org.cn:8080/news_list.asp?c_id=178&s_id=311 [Accessed 02/07/2010]
- Drake, B. & Hubacek, K. 2007. "What to expect from a greater geographic dispersion of wind farms?--A risk portfolio approach". *Energy Policy*, 35, 3999-4008.
- Enis, B., Lieberman, P. & Rubin, I. 2003. "Operation of hybrid wind-turbine compressed-air system for connection to electric grid networks and cogeneration". *Wind Engineering*, 27, 449-459.
- Fenby, J. & Qu, D. 2008. *China's Grids Power Up*. London: Trusted Sources UK Ltd.
- Goggin, M. 2008. *20% Wind Energy by 2030: Wind, Backup Power, and Emissions*. AWEA's *Wind Energy Fact Sheets*. Washington, DC: American Wind Energy Association.
- GWEC 2010. *Global Wind 2009 Report*. Brussels: Global Wind Energy Council.
- He, D., Li, Z., Ni, W., Yang, Y., Wang, Z. & Dai, H. 2008. *The Strategic Development of Renewable Energy in China - A Special Issue on Wind Energy*, [in Chinese] Beijing, China Electric Power Press.
- Higashi, N. 2009. "Natural Gas in China - Market Evolution and Strategy". *Working Paper Series: Energy Market and Security 2009*. Paris: International Energy Agency.
- Holttinen, H. 2009. *Design and Operation of Power Systems with Large Amounts of Wind Power*. Paris: International Energy Agency.
- Li, J. 2010. "Decarbonising power generation in China--Is the answer blowing in the wind?" *Renewable and Sustainable Energy Reviews*, 14, 1154-1171.
- Li, J. & Shi, L. 2006. "Brief description of hydropower resources in China". *Water Power*, 32, 3 - 7.
- Liu, L. & Yang, F. 2008. "Which wind turbine manufacturer is going to lead the market" [in Chinese]. *Wind energy development report*. Beijing: CITIC Securities Company Limited.
- McElroy, M.B., Lu, X., Nielsen, C.P., Wang, Y.X. 2009. "Potential for Wind-Generated Electricity in China". *Science*, 325, 5946, 1378 - 1380
- SERC 2009. *China's Wind Power Development Report* [In Chinese]. Beijing.
- SGCC. 2007. *Why different voltages are needed in high voltage electricity transmission system?* [Online]. [In Chinese]. Beijing. Available: <http://www.sgcc.com.cn/dlhp/dlhb/kpzs/sbdssjzbzs/61089.shtml> [Accessed 3rd July 2010].
- Wang, H. & Nakata, T. 2009. "Analysis of the market penetration of clean coal technologies and its impacts in China's electricity sector". *Energy Policy*, 37, 338-351.

- Wang, Q. & Chen, Y. 2010. "Barriers and opportunities of using the clean development mechanism to advance renewable energy development in China". *Renewable and Sustainable Energy Reviews*, 14, 1989-1998.
- White, D. 2004. *Reduction in Carbon Dioxide Emissions: Estimating the Potential Contribution from Wind-Power*. London: Renewable Energy Foundation.
- XINHUA. 2009. "China to build six 10-GW-Level wind farm bases" [Online]. [In Chinese] Beijing: Xinhua News Agency. Available: http://news.xinhuanet.com/newscenter/2009-02/16/content_10828897.htm [Accessed 3rd July 2010].
- Zhang, W., Zhou, X., Guo, J., Yin, Y., Tang, Y. & Guo, Q. 2007. "Feasibility of 1,000 kV Ultra HVDC in the Power Grid of China". *Proceedings of the Chin. Soc. for Elec. Eng.*, 27, 1-5.

DISPELLING THE MISCONCEPTION OF LOW-EROI PHOTOVOLTAICS: PEAK OIL IS HERE, LET US NOT SQUANDER WHAT IS LEFT

Marco Raugei^{*1,2}, Vasilis Fthenakis^{2,3}, Pere Fullana-i-Palmer¹

¹ Environmental Management Research Group (GiGa), ESCI - Universitat Pompeu Fabra, Barcelona, Spain

² Center for Life Cycle Analysis, Columbia University, New York, NY, USA

³ Brookhaven National Laboratory, Upton, NY, USA

ABSTRACT

Fossil fuel reserves have played a crucial role for over a century, by providing high net energy gains to fuel our societies. The Energy Return on Investment (EROI) of conventional oil and gas has been in constant decline since the 1930's, though, and the common belief has been that no viable alternatives exist to offset this trend. In particular, photovoltaic (PV) technologies have long been shunned because of supposedly low EROI. We show that the latter is an artifact of inconsistent calculations, and that switching from burning fossil fuels as feedstock in thermal power plants to using them for building large-scale PV systems would increase the associated EROI by at least one order of magnitude. Deploying large PV capacities worldwide, long before the EROI of fossil fuels eventually approaches unity, may actually be amongst the most effective strategies to reach the ultimate long-term goal of putting an end to our dependence on non-renewable energy.

Keywords: Photovoltaics, PV, EROI

1. INTRODUCTION

Energy Return on Energy Investment (EROI) has long been held as an indicator of the ultimate viability of an energy option [Cleveland et al., 1984]. The EROI of a fossil fuel has been defined as the ratio of the energy in the fuel itself (E_F) to the primary energy which was required to extract and deliver it (E_{ED}):

$$EROI_F = E_F/E_{ED} \quad (1)$$

Following decades of continuous extraction and subsequent impoverishment of the Earth's fossil fuel stocks, the EROI of oil and gas reserves have shrunk from over 100 at the beginning of last century to between 10 to 30 today, depending on the specific field and its proximity to exhaustion [Hall et al., 2008; Hall and Day, 2009]. Since the late 1970's, net energy analysts have been voicing their concern about this worrying trend, arguing that the global peak in oil production would happen shortly after the turn of the century [Campbell and Laherrère, 1998], and that we should start being more thrifty in our management of the oil and gas reserves that are left. The EROI of coal has remained relatively stable at 40 to 80, but coal is a less flexible fuel than oil or gas, cannot be directly used to power vehicles, and its combustion invariably entails higher environmental impact, in terms of greenhouse gas as well as acidic and particle emissions.

In parallel to the dwindling of fossil fuels reserves and the corresponding decrease in their average EROI, modern societies have turned more and more to electricity as the preferred vector to satisfy their end-use energy needs, because of its unsurpassed flexibility, transferability and cleanness at the point of use. This has only exacerbated the problem, since to date over 80% of the world's electricity is generated in thermal plants, which use essentially 100-year old technology to burn fossil fuels and use roughly 30% of the resulting thermal energy (the rest being irreversibly lost as waste heat) to turn water

* Corresponding author; E-mail: marco.raugei@esci.es

into high-pressure steam and run a turbine. Most of the remaining 20% of the world's electricity is produced in hydroelectric dams, which themselves are not free from environmental side-effects, and in any case cannot be easily scaled up because of geographical constraints. Geothermal electricity is even smaller in global potential, and most available reserves have already been tapped. Which leaves us with nuclear, and the so-called “renewable” alternatives, such as wind, biomass and photovoltaics (PV). In the existing EROI literature, though, renewables have almost invariably been downplayed as being hampered by intrinsically and inescapably low EROIs, and thus little attention has been paid to them as potential substitutes for thermal power plants. We show here that, in the case of PV, this is a misconception based on outdated energy performance data and, more importantly, inconsistent calculations, and that PV should really be looked at as a more efficient way to make use of the remaining fossil fuel reserves.

2. A MATTER OF CONSISTENCY

In order to evaluate if and to which extent PV represents today a viable alternative to thermal electricity produced through the combustion of fossil fuels, it is first and foremost of paramount importance to perform the comparison in a consistent fashion, i.e. adopting the same system boundaries and equations. Unfortunately, this does not appear to have been the case in the hitherto published scientific literature.

2.1 EROI of thermal electricity

The EROI of thermal electricity has traditionally been calculated by taking the ratio of the *electric energy* in output from the power plant to the *primary energy* that was required to extract and deliver the feedstock fuel used by the plant itself. This is illustrated in Eq. 2, where E_{ED} stands for the energy used for fuel extraction and delivery, E_F stands for the energy in the feedstock fuel, and E_{el} is the output electricity.

$$EROI_{el} = E_{el}/E_{ED} \quad (2)$$

Given the definition of the EROI of the feedstock fuel above (Eq. 1), the EROI of thermal electricity can be rewritten as:

$$EROI_{el} = EROI_F * E_{el}/E_F \quad (3)$$

where $E_{el}/E_F = R$ is the heat rate of the power plant.

Assuming an average heat rate = 0.3, one can thus calculate a range for the $EROI_{el}$ of thermal electricity of 3 to 24.

2.2 EROI of PV electricity

In the published literature, it has been suggested that the EROI of PV electricity should be calculated as the ratio of its lifetime (T) to its energy pay-back time (EPBT) [Hall, 2008; Heinberg, 2009; Reich-Weiser et al., 2008]. The latter is defined as the time it takes for PV to produce the same amount of electricity that could be produced by the existing electric grid, using the same cumulative primary energy demand (CED). This can be expressed by Eq. 4:

$$EPBT = CED/SE \quad (4)$$

where SE (spared energy) is the amount of primary energy required by the grid to produce the same amount of electricity as a PV power plant produces in one year.

The advocated ratio $EROI = T/EPBT$ thus equals to $EROI = (T*SE) / CED$, where $T*SE$ is the total spared primary energy over the PV plant's lifetime.

One first observation is readily apparent: this ratio is *not consistent* with the $EROI_{el}$ as defined and calculated for thermal electricity. In fact, $EROI = T/EPBT$ is a ratio of the

primary energy that is spared from consumption by the grid to the *primary energy* that is required for the construction and maintenance of the PV plant. It therefore implies a comparison across different technologies (PV vs. the grid), and represents the ratio of two primary energy quantities. Conversely, the $EROI_{el}$ of thermal electricity is, as we have seen in section 2.2, the ratio of the *electric energy* in output from the power plant to the *primary energy* required for the extraction and delivery of the fossil fuel used as feedstock in that same plant.

Moreover, it should be noted that the most recent updates on the EPBT of modern PV point to EPBTs for the complete systems ranging from 2 to 0.8 years [Fthenakis et al., 2009; Fthenakis and Alsema, 2006], and that all commercial systems are guaranteed to work for a minimum of 30 years. Thus, even applying this inconsistent formula, the EROI of modern PV would still lie between 15 to 37.5.

Such results cannot and should not be directly compared to those for thermal electricity, though, because of the inherent methodological inconsistency explained above. Instead, the same system boundaries and methodological approach should be applied in the calculation of the EROI of both thermal and PV electricity, as illustrated in Figure 1.

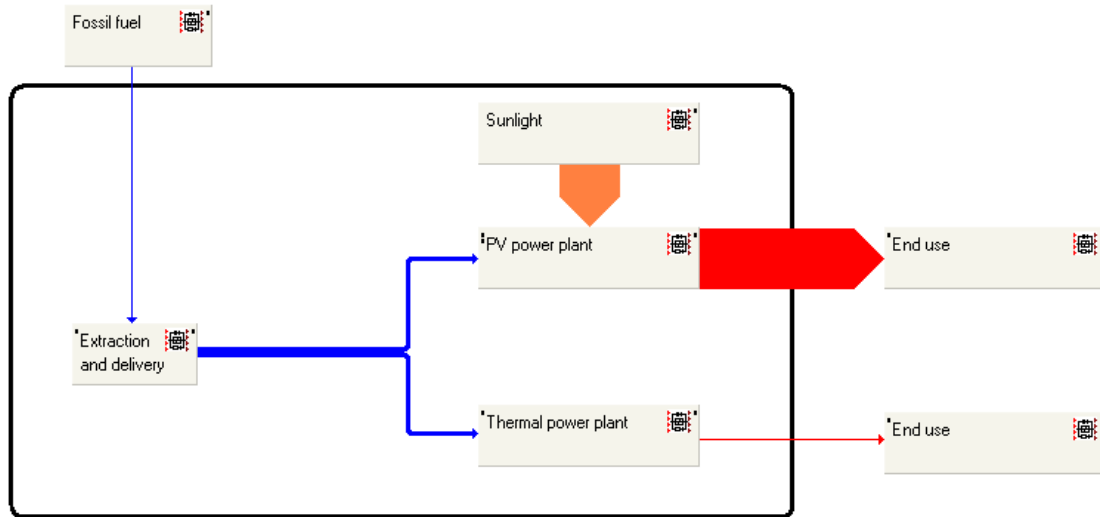


Figure 1. Flow diagram for thermal vs. PV electricity generation. Arrow thicknesses are proportional to energy flows.

Let us recall Eq. 3 from section 2.2 above: $EROI_{el} = EROI_F * E_{el}/E_F$

We may take an average $EROI_F = 40$ for the mix of fossil fuels used for the construction and maintenance of the PV plant, and then calculate E_{el} (total electricity produced during the PV plant's lifetime) and E_F according to Eqs. 5 and 6 below.

$$E_{el} = E_s * \eta * PR * T \quad (5)$$

where:

E_s = solar energy input per year;

η = module efficiency;

PR = performance ratio (which takes into account all system efficiency losses);

T = PV plant lifetime.

$$E_F = CED - E_{ED} = CED - E_F/40 = 40/41 * CED \quad (6)$$

where CED = cumulative energy demand of PV power plant.

Using the world average solar irradiation [NASA, 2008] and up-to-date values for η , PR, T and CED [Fthenakis et al., 2009; Fthenakis and Alsema, 2006] leads to an $EROI_{el}$ for PV electricity ranging from roughly 100 to 700, depending on the specific PV technology.

We argue that these are the only EROI numbers for PV that can be meaningfully compared to those for conventional electricity, since both are ratios of *electric energy output to primary energy input* for fuel extraction and delivery, and both are based on the same equations and are calculated with consistent system boundaries.

In fact, this comparison sheds light on what should have been clear all along, i.e. that photovoltaics should not (yet) be looked at as an alternative energy source vs. fossil fuels, but rather as an alternative energy transformation process vs. thermal electricity production. If looked at this way, it becomes quite apparent that deploying fossil fuels in PV is far more efficient than burning them directly at roughly 30% efficiency to produce electricity in conventional power plants (which of course is due to the ability of PV to harness a second energy source, i.e. sunlight).

3. A LOOK AHEAD

Current PV technologies are improving fast, and new, more efficient, technologies may become available in the future. However, none of these PV technologies can serve as base-load electricity sources on their own, because of the intrinsic intermittency of solar power generation. Recent prospective studies have shown that deploying PV on a large scale beyond 20% grid penetration will require establishing an extensive energy storage infrastructure [Denholm and Margolis, 2006]. Even if potentially feasible, the latter will likely be costly, both in economic and energy terms, and will inevitably drag down the medium-term EROI of such PV-storage ensemble.

One further strategic issue is that of short-term power return per unit of energy invested. Put it simply, PV takes years to give back all the electricity it can produce, while the energy investments to deploy it will largely have to be made up front.

However, in spite of all these lingering issues and looming problems, the fact remains that using fossil fuels for the production of PV power plants is, today, at least one order of magnitude more energy-efficient than burning the same fuels in conventional thermal power plants, and this advantage will remain even as the EROI of oil and gas go down. If large enough investments in PV are made early enough, the additional energy return from PV electricity vs. today's mostly thermal grid may afford us valuable time in our race against time after peak oil. In fact, being pro-active and deploying large PV capacities worldwide, long before the EROI of fossil fuels eventually approaches unity, may even end up being amongst the most effective strategies to reach the ultimate long-term goal of putting an end to our dependence on non-renewable energy.

REFERENCES

- Campbell C.J., Laherrère J.H. "The End of Cheap Oil". *Sci. Am.* 1998, 278:78-83
- Cleveland C.J., Costanza R., Hall C.A.S., Kaufmann R. "Energy and the U.S. Economy: A Biophysical Perspective." *Science* 1984, 225:890-897
- Denholm P., Margolis R.M. "Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies". *Energy Policy* 2006, 35:4424-4433.
- Fthenakis V.M., Alsema E. "Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs: 2004–early 2005 Status". *Prog. Photovolt. Res. Appl.* 2006, 14:275–280
- Fthenakis V.M., Held M., Kim H.C., Raugei M. "Update of Energy Payback Times and Environmental Impacts of Photovoltaics". *24th European Photovoltaic Solar Energy Conference and Exhibition; Hamburg, Germany, 2009*
- Hall C.A.S., Day J.W. "Revisiting the Limits to Growth After Peak Oil". *Am. Sci.* 2009, 97:230-237
- Hall C.A.S., Powers R., Schoenberg W. "Peak Oil, EROI, Investments and the Economy in an Uncertain Future". In *Biofuels, Solar and Wind as Renewable Energy Systems: Benefits and Risks*; Pimentel D., Ed.; Springer Science: The Netherlands, 2008; pp 504
- NASA Atmospheric Science Data Center. *Surface meteorology and Solar Energy: Global Data Sets*, 2008; <http://eosweb.larc.nasa.gov>

SESSION 2.2

CHALLENGES OF FUTURE ELECTRICITY SUPPLY

Müller J., Rommel J.

IS THERE A FUTURE ROLE FOR URBAN ELECTRICITY COOPERATIVES?
THE CASE OF GREENPEACE ENERGY

Ghisellini P., Rota C., and Ulgiati S.

ENVIRONMENTAL, ECONOMIC AND FINANCIAL UNCERTAINTIES OF
NUCLEAR ELECTRICITY

Gabarrell X., Amat E., Oliver Solà J., Gasol C. M., & Rieradevall J.

THE EFFECTS OF USING DIFFERENT MIXES OF ENERGY SOURCES IN THE
GENERATION OF ELECTRICITY IN EUROPE

IS THERE A FUTURE ROLE FOR URBAN ELECTRICITY COOPERATIVES? THE CASE OF GREENPEACE ENERGY

Jakob Müller^{*1}, Jens Rommel²

¹ *Institute for Corporate Governance, Faculty of Economics and Management, University Witten/Herdecke and Division of Cooperative Sciences, Department of Agricultural Economics, Humboldt University Berlin*

² *Division of Resource Economics, Department of Agricultural Economics, Humboldt University Berlin*

ABSTRACT

In his seminal book “The ownership of Enterprise”, Henry Hansmann develops a theory of “ownership costs”. One chapter deals with utilities. As network utilities are “natural monopolies” they have some advantages in cooperative organization. Hansmann argues that these advantages unfold only in rural areas. Contrary to this proposition, in Germany we are observing an increasing number of urban electricity cooperatives. In this paper we develop a typology of ten external factors that have had an impact on the power sector and which have undergone change in the last years. We argue that this change in external conditions had an impact on ownership costs and therewith on the organization of enterprise in the power sector. We relate these factors to an urban electricity cooperative: Greenpeace Energy. From an explorative case study analysis we find that there are two important factors that foster the foundation of cooperatives: differentiation of electricity products and the increasing importance of consumer–producer relations. In both cases cooperatives can overcome information asymmetries by the identity of users and owners. The paper ends with preliminary policy implications for cooperative law and implications for further research.

Keywords: Cooperatives; Electricity; Greenpeace Energy; Henry Hansmann; Hybrids; Ownership Costs

1. INTRODUCTION

In Chapter 9 of his seminal book “The ownership of enterprise”, Henry Hansmann (1996) argues that because of the natural monopoly of networks, the cost-efficient form of electricity utility organization is the cooperative. However, he limits his argument to rural areas. In urban areas electricity cooperatives may be difficult to organize, due to higher costs of ownership. Contrary to this proposition, in urban areas of Germany and other European countries we are observing an increasing number of generation and trading cooperatives (Olsen and Skytte, 2002; Klemisch and Maron, 2010). In this paper we argue that this positive observation can be explained by a change in exogenous factors which have an impact on the ownership costs of the power industry. More specifically, we are trying to show that some of these factors have decreased ownership costs for electricity cooperatives vis-à-vis other organizational forms. Based on Hansmann's differentiation between three types of ownership costs, “the costs of controlling managers, the costs of collective decision making, and the costs of risk bearing” (Hansmann, 1996, p.35), we are developing a typology of these factors. In our analysis we focus on electricity *generation* and *trading*. We explicitly exclude electricity networks and distribution from the analysis. The core of our analysis is based on a case study on one of the largest electricity trading cooperatives in Germany: Greenpeace Energy. From a document analysis and two interviews with a member from the supervisory board (1) and the head of the

* Corresponding author; E-mail: jakob.mueller@uni-wh.de

management of member relations (2), we are trying to identify the factors, which are important for cooperatives relative to other organizational forms of entrepreneurship.

The remainder of this paper is organized as follows. In the next section we will give a short overview on the relevant literature. We are going to start from the New Institutional Economics and more specifically The Theory of the Firm literature to explain what the specific properties of cooperatives are. We will then relate Hansmann's concept of ownership costs to this literature. We will proceed with applying Hansmann's argument to the case of urban electricity cooperatives in Germany. In section 3 we intend to introduce and categorize the recent exogenous changes, which we assume to have an effect on ownership costs and therewith on the organizational form of electricity utilities. In section 4 we are going to introduce a method to approach the empirical part of our research question. In section 5 our case, the Greenpeace Energy Cooperative, will be presented. In this section we are also going to present and discuss the results of our analysis. In the last section we will conclude.

2. LITERATURE

2.1 The Cooperative from a New Institutional Economics Perspective

"A co-operative is an autonomous association of persons united voluntarily to meet their common economic, social, and cultural needs and aspirations through a jointly-owned and democratically-controlled enterprise" (ICA, 2010). This definition hits the core of various types of cooperatives being characterized by their democratic decision structure (one member one vote) and their joint ownership of assets. The self-organizing and self-help character of cooperatives encompasses the personal identity of different stakeholders. Customers are at the same time investors, owners and may be managers, which is a major difference to most investor-owned firms (IOFs).

The different perspectives on cooperatives described in the literature build an own sphere of theories (Chaddad, 2009). The Theory of the Firm, for example, characterizes cooperatives as "ordinary" profit-maximizing firms. The only thing that is special about cooperatives is that they incorporate outsourced attributes of their owners, such as demand or supply functions (Feng and Hendrikse, 2008). This argumentation would not differentiate between cooperatives and IOFs (Helmlinger and Hoos, 1962).

Contrary to this view Transaction Cost Economics distinguishes markets, hierarchies and hybrids as organizational forms (Williamson, 1991). IOFs are classified as hierarchies, whereas cooperatives are hybrids (Ménard, 2007), because they entail properties of markets *and* hierarchies (Chaddad, 2009). "The central characteristic of hybrids is that they maintain distinct and autonomous property rights and their associated decision rights on most assets, which makes them different from integrated firms; however, they simultaneously involve sharing some strategic resources, which requires a tight coordination that goes far beyond what the price system can provide and thus makes them distinct from pure market arrangements" (Ménard, 2007, p.6). Distinct features of hybrids are the pooling of assets, the significance of a contract that coordinates their members, and the avoidance of ruinous competition (Ménard, 2007).

Other authors argue that the particular feature of a cooperative is the ability to overcome certain difficulties of other organizations, such as hold-up problems or information asymmetries (Bonus, 1986; Hendrikse and Veerman, 2001). The view of Hansmann (1996) differs from all these theories of the cooperative. For him the cooperative is an ownership type of enterprise. Ownership costs are the determining element of organizational form. The identity of different stakeholders in cooperatives minimizes market contracting costs, but causes ownership costs at the same time.

2.2 Ownership Costs and Organizational Form

In his book "The Ownership of Enterprise", Henry Hansmann (1996) develops a theory of ownership costs associated with different organizational forms of entrepreneurship. In the tradition of The Theory of the Firm he argues that the "diverse pattern of ownership" (p.2), i.e. a large variety of organizational forms, may be explained in the light of what he calls "costs of ownership". For Hansmann (1996) the firm is a "nexus of contracts". Unlike for instance Oliver Williamson (1975, 1985, 1991), he does not differentiate between markets and hierarchies, but between contracts that exist in either the market or the ownership context. Both types of contracts are associated with different contracting costs. "Assigning ownership of a firm to one or another class of the firm's patrons can [...] often reduce the costs of transacting with those patrons" (Hansmann, 1996, p.21). On the other hand, "[i]f ownership were always perfectly effective, in the sense that it eliminated all costs of market contracting without imposing any new costs of its own, then there would be no more to a theory of ownership than this. In fact, however, ownership itself involves costs" (ibid., p.21). These countervailing forces of benefits and costs of ownership suggest that there is an optimal point of ownership assignment "that minimizes the total costs of transactions between the firm and all of its patrons" (ibid., p.21). Thus, a cost minimizing enterprise will assign ownership to those patrons "for whom the problems of market contracting [...] are most severe" (ibid, p.21). Hansmann distinguishes between three types of ownership costs: Costs of Collective Decision Making, Costs of Risk, and Agency Costs. We are building our argument along this categorization.

The first two types are related to the control of the firm. The costs of monitoring the management, the costs of opportunistic managers (agency costs), and coordination costs depend on ownership assignment. Similar to an IOF, risk bearing costs are related to the claims on the enterprise's residual earnings. They are basically associated with the firm's capital lenders. Hansmann, however, extends the argument. He points out that also a firm's customers can bear risks. The extent of these costs and the share in the customer's budget are important factors that determine assignment of ownership.

For Hansmann these costs explicitly include a number of non-pecuniary costs. These are the costs of "governance", e.g. for reaching collective agreements or monitoring managers (ibid., p.21). He also points out that "the feeling of ownership" can have a value of its own, if for example "the costs of contracting for labor on the market might be a subjective sense of alienation or disempowerment that could be alleviated if the workers instead owned the firm" (ibid., p.23).

In Chapter 9 of his book Hansmann (1996) discusses why utilities are organized as cooperatives mainly in rural areas. Starting from the point that utilities are typically "natural monopolies", he argues that the costs of market contracting are very high. Monopoly pricing would hit consumers hard. Moreover, the costs of rate regulation are lower if interests of the firm's owners and customers are aligned. Contracting costs can be reduced if ownership is assigned to customers, i.e. a consumer cooperative is formed. Moreover, entrepreneurial risk in the case of utilities is relatively low as demand for their services is rather stable over time. In practice Hansmann observes utility cooperatives only in rural areas. He points out that rural areas differ sharply from cities and towns. First, urban cooperatives do not receive subsidies, as it is the case, for instance, for rural electrification cooperatives in the United States. This fact, however, represents only insufficient reasoning for the existence of rural cooperatives (Hansmann, 1996, p.174). Second, urban customers are more transient. In other words, they change their location more frequently and they own real estate less frequently. Thus, capitalization of infrastructural investments into real estate would benefit the landlord, not the tenant. In the language of Hansmann this incentive problem means an increase in Costs of Risk in urban areas, relative to rural areas. Third, urban consumers are more heterogeneous. While in rural areas potential cooperative members are likely to share a common pattern of demand for the desired service, in urban areas consumers may fall into distinct classes

of residential, commercial, and industrial consumers. In the latter case, the dominating group could try to impose rates that cross-subsidize their own services on the expense of other groups. In such a situation costs of collective decision-making are likely to exceed the benefits of cooperative organization.

In 1996, Hansmann based his argument on electricity companies that were fully integrated along the electricity value chain. Generation, distribution, and trading activities were all organized within the same organization. These companies possessed distribution networks which indeed are a natural monopoly and enabled them to charge monopoly prices. Consequently, regulation referred to the fully integrated company and could not be concentrated on the network entity until unbundling took place (Mittendorf, 2006). Since then many new market entrants – among them many cooperatives – have entered the field, especially in the area of generation and trading (Olsen and Skytte, 2002). A review of Hansmann's reasoning is thus necessary. In his argument he refers to the cooperative ownership of physical network infrastructures and the associated natural monopoly. In this area Hansmann's argument is still valid. At least in Germany there are still no established network cooperatives in urban areas. In the area of generation and trading, the transience of city dwellers is no longer a hindering element to cooperatives, as it is possible to keep one's electricity supplier when moving. The separation of ownership and control in the case of tenants does not increase the cost of risk when joining purchasing cooperatives. Also, the heterogeneity of the urban population does not impede urban electricity cooperatives. Unlike for the distribution (network) part of the supply chain, customers can freely choose between numerous suppliers. They can easily group themselves into smaller and more homogenous sub-units for generation and trading. The decrease in scale economies of energy technologies adds to these trends.

We can conclude that Hansmann's proposition of the absence of urban electricity cooperatives needs to be partly revised. After vertical desintegration of utilities, transience and heterogeneity are no more inhibiting factors for electricity cooperative formation in urban areas. At the same time, the question arises why so many electricity cooperatives are newly formed. Why is the field of electricity purchasing and generation not solely dominated by IOFs or other organizational forms? The next section is dedicated to the presentation of a typology of recent developments which affect ownership costs of electric utilities. These factors may explain a good deal of the new organizational diversity of the power industry.

3. A TYPOLOGY OF EXOGENUS CHANGE IN THE POWER INDUSTRY

A number of political, economical, social and technological factors with an impact on the organization of electricity generation has undergone radical change in the last two decades. There are now more than 140 newly founded energy cooperatives in Germany (Genossenschaftsverband, 2009). From this positive observation, we argue that exogenous change had an impact on ownership costs and therewith on the organization of enterprise.

In the following section we are trying to develop a typology of these dynamic factors with regard to the governance of the electricity enterprise and the costs of ownership. In Table 1 we have summarized the factors that we have identified. We grouped them into political, economic, social, and technological factors and the three different categories of ownership costs distinguished by Hansmann.

Table 1. A typology of factors with an impact on ownership costs of electricity cooperatives

	Collective decision cost	Agency cost	Cost of risk
Political factors	(1) Revised coop law		(4) Renewable Energy Act, (5) Regulation and unbundling
Economic factors	(2) Need for local investments and jobs	(6) Differentiation of energy, (7) Interaction producer and consumer	(8) Externalities of renewables

Social factors	(3) Entrepreneurial civil society	(9) Change in owner tenant relationship
Technical factors	(10) Small scale generation	

Of course, these categories are not clear-cut and may also be interrelated. Small-scale generation of renewable energy in a cooperative, for instance, may depend on the Renewable Energy Act, technical developments, and the revised cooperative law, allowing smaller units to work efficiently. These factors then affect both costs of risk and collective decision making. We will now explain the factors in more detail.

(1) In the year 2006, the cooperative law in Germany has been revised. Changes in favor of smaller cooperatives have been implemented. Nowadays, to form a cooperative it needs only three instead of the formerly seven members. The rules for supervisory boards have been relaxed. Cooperatives with less than 20 members do not need to form a supervisory board anymore. The board of small cooperatives can consist of only one director and decision-making of the general assembly have been made easier. Cooperatives with a turnover of less than 2 million Euros or less than 1 million Euros of total balance sheet assets are relieved from the special auditing obligations of German cooperatives (Genossenschaftsverband, 2010). Similar changes are taking place in other developed countries. The demand for more flexible institutions for cooperative organizations, as for example deviations from the one-member-one-vote principle, are reflected in the scholarly debate on so-called "New Generation Cooperatives" (Cook, 1995; Cook and Iliopoulos, 1999; Chaddad and Cook, 2004). These new developments are likely to lower administrative and decision making costs of cooperatives. Lower group sizes, for instance, may exert a positive effect on collective action problems (Olson, 1965).

(2) Another factor that has been widely discussed in the last years is the increasing need of local investments. Indebted communities are looking for ways to create local jobs or reduce debts. Cooperatives can play an important role in this regard. They are able to form the organizational body for such local investments from community members. Local governments often support the foundation of community-based enterprises. This catalyzing effect may lower decision making costs. Cooperative organization of key public services may be a viable option especially in rural areas (Hanisch, 2009). This does not mean, however, that services such as water or electricity provision cannot be organized as a cooperative in towns, cities, or even megacities (Morse, 2000; Klemisch and Maron, 2010; Hanisch et al., forthcoming).

(3) Civil society activities have strongly grown in the last years. To channel the engagement of an entrepreneurial civil society which is interested, for instance, into the generation of renewable energy, can best be achieved by a cooperative in close collaboration with the local administration (Klemisch and Maron, 2010). To organize these services as local cooperatives has several additional advantages, for example a higher acceptance of customers (Walker et al., 2007; Walker, 2008).

(4) The renewable energy feed-in tariff guarantees producers of renewable energy fixed prices over long periods. Therewith, it lowers the cost of risk associated with ownership of generation capacities (The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany, 2010). This factor may not be very cooperative-specific. Yet, the impact may be strong in combination with other factors.

(5) The regulation and unbundling activities have led to a more stable and non-discriminating market environment. Entrepreneurial activity on the electricity market is not facing monopolistic powers anymore. This lowers the risk costs of ownership and had a significant impact on the number of consumer-owned and municipality-owned utilities (Olsen and Skytte, 2002).

(6) The demand for green energy has increased. For consumers it is often not transparent where and how energy is produced. Agency costs of market transactions have increased relative to the agency costs of ownership. Similar to the argument brought up for credit cooperatives (Bonus, 1986) or quality uncertainty of water (Morse, 2000),

electricity cooperatives may reduce information asymmetries, for example on the origin of supply.

(7) Combined heat and power generation, efficiency contracting, and smart grids, all result in interdependencies between producers and consumers. Even though these factors have not yet come to their full effect, they are likely to reduce agency costs of ownership in the future. Beside these technical developments one can identify a rising interaction between consumer and producer in the area of energy efficiency. Feedback on energy use (Gleerup et al., 2010) and involvement of customers into decision making on energy supplies will add to the importance of this factor.

(8) Almost all renewable energy sources, as for instance on-shore wind farms, have negative externalities. Assignment of ownership to the aggrieved party can internalize some of these costs and lower the risk of owners (Morse, 2000).

(9) Another prevailing trend, especially in urban areas, is the change of the relationship between owner and tenant. Tenants are more frequently becoming owners. Owner-communities of apartment houses have their own small-scale generation capacities for heat and power generation. As a consequence, agency cost can be reduced by ownership assignment.

(10) Contrary to large coal or nuclear power plants, small scale generation technologies allow for a small number of investors with few resources to found a jointly owned and controlled enterprise. A smaller number of investors also means lower cost of collective decision making (Olson, 1965) and hence lower costs of ownership.

In the next section we will explain our method and then relate these factors to our case.

4. THE CASE STUDY METHOD

Following Yin (2009, p.8), determining the adequate method in social sciences can be done by distinguishing between three conditions: the form of the research question (1), the requirement to control for behavioural events (2) and the focus on contemporary events (3). The respective categorization of one's research will determine if an experiment, a survey, an archival analysis, a history, or a case study is the appropriate way of approaching the research question. If one is asking a "how or why question", there is no need to control of behavioural events, and if one is focusing on a contemporary phenomenon, a case study approach is the best way to address an empirical research question. All of these three conditions are met in our case: We are asking *why* we are observing new electricity cooperatives even in urban areas, we do *not* require behavioural control as in a (clinical) experiment, and we are interested in a *contemporary* phenomenon which is embedded in a social context. The unit of analysis in our case is the cooperative.

We are asking why urban electricity cooperatives emerge? What are the main factors behind this development? What are the main drivers that reduce ownership costs? We base our study on the analysis of annual reports and personal interviews. The logic behind linking the data and our proposition is, that if changes in the electricity market had an impact on ownership costs, then the history of electricity cooperatives must reflect these changes as key drivers for their emergence. To mark the relative importance of the ten key factors we have identified, we make use of a subjective seven point scale in the interviews, where 1 means the lowest and 7 the highest possible impact on ownership costs of electricity cooperatives. Due to limited space we refer the reader to Yin (2009) for further information on the case study method.

5. THE CASE OF GREENPEACE ENERGY

We have chosen Greenpeace Energy because it is the largest renewable energy trading cooperative in Germany. It was one of the first newly founded enterprises after liberalization of the electricity sector in 1998. Greenpeace Energy is not affiliated with the

NGO Greenpeace, though it was founded by Greenpeace members. However, Greenpeace Energy is allowed to use the name Greenpeace for marketing purposes. It was founded in October 1999. In 2009 it produced 318 Giga Watt hours, had 18,100 members, 94,000 customers, and employed 62 people. The turnover in 2009 was about 86.7 million Euro (Greenpeace Energy, 2010). From the document analysis we found out that a few factors, highly identical with the exogenous changes in electricity markets we identified above, determined the founding and growth of the cooperative.

In most annual reports of Greenpeace Energy the importance of the legal framework, especially the renewable energy law (4) with its guaranteed feed-in tariff, and regulation and unbundling (5) were mentioned to have played a major role for the success of the cooperative (Greenpeace Energy, 2002, 2003, 2005, 2006, 2007, 2009). Beside this, the differentiation of energy by generation sources (6) and a broad interest for the origin of electricity, were frequently cited success factors for the growth of the cooperative (Greenpeace Energy, 2002–2009). Also, increasing entrepreneurial civil society engagement (3) has played a role (Greenpeace Energy, 2006–2009). Interactions between producer and consumer (7) have also been mentioned as a driving force of growth (Greenpeace Energy, 2003, 2004, 2005, 2007, 2008). The development of small scale generation systems (10) has been stated in two yearly reports (Greenpeace Energy, 2002, 2006). All these factors were identified to have a positive effect on ownership assignment to electricity consumers.

We have conducted two telephone interviews with key informants of Greenpeace Energy. To get an outside perspective on the cooperative, we have interviewed a supervisory board member who was at the same time an expert for cooperatives in general. The second respondent is responsible for the management of member relations. As a long-time employee in this area, he has also been a rich source of insider information.

The interviews were divided into two parts. In the first part we have asked questions concerning Greenpeace Energy. In the second part we have asked for electricity cooperatives in general. The interviews started with a question about the number of cooperative members from rural and from urban areas. Unfortunately, both were not able to quote exact figures, but stated that the vast majority of their members came from urban areas. Both respondents reported that at least 80% of Greenpeace Energy's members live in towns or big cities. Greenpeace Energy has a clear focus on urban areas and can be best described as an urban cooperative. The exact geographical dispersion of the cooperative members is of course not known.

The next central question concerned the motives of customers to become a member. After all, almost 20% of customers are members. Both respondents mentioned the political motivation of customers. Most members are well-educated, interested in energy issues, and politically active. With their participation members want to make the cooperative financially and economically more independent. Contrary to the motivation for investments into IOFs, claims on the residual earnings were not mentioned as a motivating factor. Rather, the members want to participate actively in the design of renewable energy supply, which is reflected in the high level of member activity. Ownership of one's own utility is a highly motivating factor to become a member. Additional information about the cooperative are made available to members, while customers have to explicitly ask for it.

These responses can be interpreted as evidence for the effect of the above mentioned factors. Cooperative members in cities want to jointly own their utility to reduce agency costs (more control over the way of generation) and to reduce the costs of collective decision making by organizing their common interest in a cost-efficient way.

In the second part of the interview we asked the respondents not only to focus on Greenpeace Energy, but to have in mind the many other newly founded electricity cooperatives. Figure 1 displays the answers of the two interview partners on a scale of 1 (lowest importance) to 7 (highest importance) for the ten hypothetical factors. The two respondents rate the importance of four of these factors within the range of one point, for

three of them there is no consent (difference greater than 2 points). One question (local value addition) could not be answered by the second interview partner. The first interview partner had a mean ranking of 5, the second of 4.7. These figures are important to cross-check the relative importance of the various factors. If these answers reflect the true importance, they also show that a large number of factors are of high importance and that there are only very few factors that are irrelevant to newly formed electricity cooperatives. Figure 1 also shows the frequency of the respective factors in the document analysis.

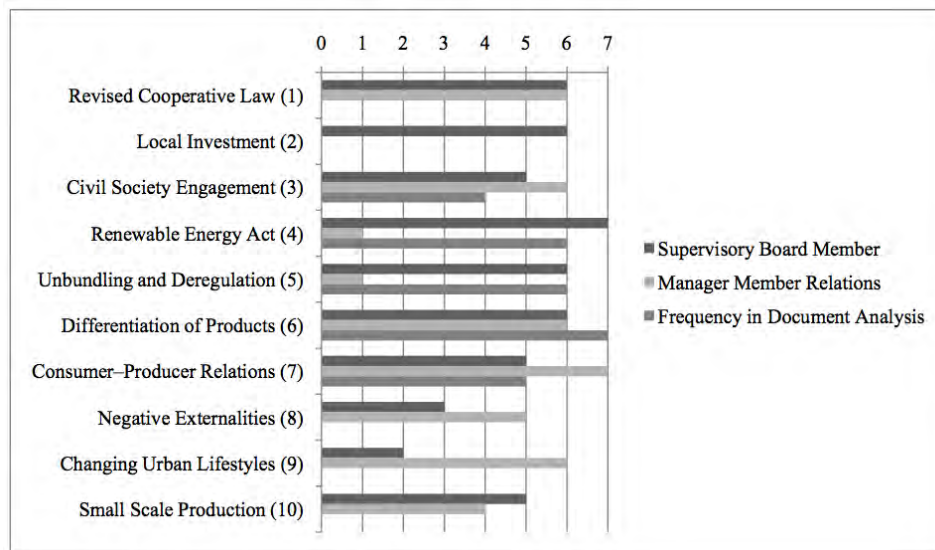
For both respondents the importance of the revised cooperative law (1), civil society engagement (3), differentiation of energy products (6), and consumer–producer interactions (7) are equal to or above the average ranking. Both interview partners use the highest possible ranking only one time. One does this for the Renewable Energy Act (4), the other for consumer–producer interactions. Astonishingly, the Renewable Energy Act (4) is ranked the lowest by the other respondent. He argues that the recent growth of cooperatives is a rather new phenomenon, from within the last five years or so. The Renewable Energy Act (4), however, is already more than eleven years old. In his view, a growth of cooperatives would have been observable much earlier if this was a key factor. Both interview partners rank the importance of consumer–producer interactions (7) relatively high. The importance of upcoming new technologies such as smart grids were ranked high by both respondents, but additional explanation during the interview relativized the actual importance of this factor. The respondents claim that this factor will become more important in the near future. They see a significant advantage for cooperatives in this regard.

If we take the average ranking, it turns out that the revised cooperative law (1), product differentiation (6), and consumer–producer interactions (7) are ranked highest with an average of 6, directly followed by civil society engagement (3) with 5.5. Unfortunately, we received only one answer for local value addition (2) which also was 6. The lowest ranked factor is unbundling (5) with 3.5. However, there is no agreement between the two respondents. In the view of the second respondent, deregulation does not go far enough. Competition is still limited. If there was more, there would be more electricity cooperatives. This gives the factor a much higher importance than the number reveals, which is in line with the findings from the annual reports.

Summarizing the interviews, the most important factors are the new cooperative act (1) and product differentiation (6). Producing one's own electricity seems to make a difference. The electricity produced by a cooperative feels different from electricity purchased from a private company. Information asymmetries may have been reduced. Another important factor is consumer–producer relations (7). The use of smart grids, variable tariffs, and good access to customer information, favor cooperative organization. Assigning ownership of an electricity utility to customers lowers the costs of obtaining customer information.

If we compare the document analysis and the interviews, we find the best match on the factors differentiation (6) and consumer–producer relations (7). Obviously, it matters *how* electricity is produced. Cooperatives may reduce information asymmetries and knowledge of consumers may be easily accessible for producers. The identity of stakeholders – consumers are their own producers – may be the best suited way to organize electric utilities in this regard. These findings are in line with the theory on cooperatives, in particular with those authors that argue from an information cost perspective. For the other identified factors there is no such clear picture from our limited evidence.

Figure 1. Relative importance from interviews and frequencies from the document analysis of factors



6. CONCLUSION

Today, in developed countries like Germany we are observing a wide spectrum of organizations in the power industry. Particularly, we see a strong growth of electricity cooperatives, also in urban areas. In this paper we have shown that Henry Hansmann's argument on the difficulty to organize urban electricity cooperatives needs to be revised. Hansmann's theory seems to be correct for the distribution part of the electricity value chain. However, it is not fully valid anymore for generation and trading. There are no more hindering factors for urban generation and trading cooperatives. Taking this into consideration, we have asked why so many cooperatives have been founded relative to other organizational forms. As a possible explanation, we assumed external factors and their impact on ownership costs to have played a key role in this development. Bearing that in mind, we explained from within Hansmanns theory why there are more cooperatives in the electricity industry now – independent from their geographic location.

In our analysis we have developed a typology of ten factors related to ownership costs and therewith to the organization of enterprise. We have focused on their relative impact on cooperative organization of electricity utilities. From our first explorative results we can conclude that the growth of electricity cooperatives is partly caused by the differentiation of electricity products and upcoming technologies that depend on consumer-producer relations. Here, cooperatives have a major advantage vis-à-vis other organizations. Assigning ownership to customers reduces information costs significantly, which is in line with the theory on cooperatives. For the other factors there is only mixed evidence. The identified developments, however, benefit cooperatives in both rural and urban areas. Our initial question why there are so many newly formed *urban* cooperatives may thus not be answered by looking at the differences between rural and urban cooperatives, but rather by looking at the differences between cooperatives and other organizations. If our findings are correct, the future growth of cooperatives in urban areas will not take place on the expense of rural cooperatives. Rather, we will observe an increasing number of cooperatives relative to other organizations and independent from their particular location. The policy implications of our findings are straightforward. If customers are highly sensitive to uncertainties with regard to the origin of their electricity, or if new technologies such as smart grids and variable tariffs are gaining further momentum, in many cases, cooperatives are likely to be the cost-efficient organizational solution for electric utilities. Policy makers could, for example, reduce the administrative

burdens for electricity cooperatives. With the revision of the cooperative law in Germany, some first steps into this direction have already been taken.

To explore this topic in more depth, further research is needed. As this paper is solely based on a document analysis and subjective interviews, conducting an in-depth study on the demand side could broaden the perspective. Eliciting consumer preferences with respect to the organizational form of electric utilities in the light of the factors that we have identified could yield further insights into this interesting research area. Additionally, one could investigate whether the governance of the newly founded cooperatives assures stable efficiency of these hybrid forms of organization compared with their non-cooperative counterparts.

ACKNOWLEDGEMENTS

We would like to thank Greenpeace Energy eG for their support. We are especially thankful to our interview partners for sharing their time and knowledge. We also would like to thank Sophia Opperskalski, Julian Sagebiel, and Cathrin Scheer for valuable comments.

REFERENCES

- Bonus, H. (1986). "The Cooperative Association as a Business Enterprise: A Study in the Economics of Transactions". *Journal of Institutional and Theoretical Economics*, 142, 310–339.
- Chaddad, F. R. (2009). *Both Market and Hierarchy: Understanding the Hybrid Nature of Cooperatives*. Paper prepared for the International Workshop "Rural Cooperation in the 21st Century: Lessons from the Past, Pathways to the Future", Rehovot, Israel, June 15–17, 2009. Retrieved August 31, 2010, from <http://departments.agri.huji.ac.il/economics/en/events/p-chaddad.pdf>.
- Chaddad, F. R., & Cook, M. L. (2004). "Understanding New Cooperative Models: An Ownership–Control Rights Typology". *Review of Agricultural Economics*, 26(3), 348–360.
- Cook, M. L. (1995). "The Future of U.S. Agricultural Cooperatives: A Neo-Institutional Approach". *American Journal of Agricultural Economics*, 77(5, Proceedings Issue), 1153–1159.
- Cook, M. L., & Iliopoulos, C. (1999). "Beginning to Inform the Theory of the Cooperative Firm: Emergence of the New Generation Cooperative". *LTA (The Finnish Journal of Business Economics)*, 4/99, 525–535.
- Feng, L., & Hendrikse, G. W. J. (2008). "On the Nature of a Cooperative: A System of Attributes Perspective". In G. Hendrikse, G. Cliquet, M. Tuunanen, & J. Windsperger (Eds.), *Strategy and Governance of Networks. Cooperatives, Franchising, and Strategic Alliances* (pp. 13–26). Heidelberg: Springer.
- Genossenschaftsverband (2009). *Jahresbericht 2009*. Retrieved September 01, 2010, from <https://www.genossenschaftsverband.de/verband/presse-aktuelles/publikationen/jahrbuecher>.
- Genossenschaftsverband (2010). *Modernisiert, vereinfacht, flexibilisiert*. Retrieved August 05, 2010, from https://www.genossenschaftsverband.de/gruender/genossenschaft-gruenden/GenG_Novelle.pdf.
- Gleerup, M., Larsen, A., Leth, P. S., & Togeby, M. (2010). "The Effect of Feedback by Text Message (SMS) and Email on Household Electricity Consumption: Experimental Evidence". *The Energy Journal*, 31(3), 113–132.
- Greenpeace Energy eG (2010). *Geschäftsberichte (Business Reports) Years 2002–2009*. Hamburg: Greenpeace Energy eG. Retrieved August 23, 2010, from <http://www.greenpeace-energy.de/de/service/downloads/genossenschaft.html>.
- Hanisch, M. (2009). "Constraints on Rural Governance in the European Union: A Role for Cooperative Associations?" In V. Beckmann & M. Padmanabhan (Eds.), *Institutions and Sustainability. Political Economy of Agriculture and the Environment – Essays in Honour of Konrad Hagedorn* (pp. 127–152). Dordrecht: Springer Netherlands.

- Hanisch, M., Kimmich, C., Rommel, J., & Sagebiel, J. (forthcoming). „Coping with Power Scarcity in an Emerging Megacity: A Consumers' Perspective from Hyderabad”. *International Journal of Global Energy Issues*, in press.
- Hansmann, H. (1996). *The ownership of enterprise*. Cambridge, Mass.: Harvard Univ. Press.
- Hendrikse, G. W. J., & Veerman, C. P. (2001). “Marketing Co-operatives: An Incomplete Contracting Perspective”. *Journal of Agricultural Economics*, 52(1), 53–64.
- International Cooperative Alliance (ICA) (2010). *Information on Co-operatives*. Retrieved September 02, 2010, from <http://www.ica.coop/coop/index.html>.
- Klemisch, H., & Maron, H. (2010). „Genossenschaftliche Lösungsansätze zur Sicherung der kommunalen Daseinsvorsorge”. *Zeitschrift für das Gesamte Genossenschaftswesen*, 60(1), 3–13.
- Ménard, C. (2007). „Cooperatives: Hierarchies or Hybrids?” In K. Karantininis & J. Nilsson (Eds.), *Vertical Markets and Cooperative Hierarchies. The Role of Cooperatives in the Agri-Food Industry* (pp. 1–18). Dordrecht: Springer.
- Mittendorf, M. (2006). „Das natürliche Monopol in der Elektrizitätsversorgung”. *Wirtschaftswissenschaftliches Studium*, 5/2006, 266–272.
- Morse, L. B. (2000). “A Case for Water Utilities as Cooperatives and the UK Experience”. *Annals of Public and Cooperative Economics*, 71(3), 467–495.
- Olsen, O. J., & Skytte, K. (2002). “Consumer Ownership in Liberalized Electricity Markets: The Case of Denmark”. *Annals of Public and Cooperative Economics*, 78(1), 69–88.
- Olson, M. (1965). *The logic of collective action: Public goods and the theory of groups*. Cambridge, Mass.: Harvard Univ. Press.
- The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety Germany (2010). Erneuerbare-Energien-Gesetz. Retrieved August 25, 2010, from http://www.bmu.de/erneuerbare_energien/erneuerbare-energien-gesetz/doc/40508.php.
- Walker, G. P., Hunter, S., Devine-Wright, P., Evans, B., & Fay, H. (2007). “Harnessing community energies: Explaining and evaluating community-based localism in renewable energy policy in the UK”. *Global Environmental Politics*, 7(2), 64–82.
- Walker, G. (2008). “What Are the Barriers and Incentives for Community-owned Means of Energy Production and Use?” *Energy Policy*, 36(12), 4401–4405.
- Williamson, O. E. (1975). *Markets and hierarchies: Analysis and antitrust implications: A study in the economics of internal organization*. New York, NY: The Free Press.
- Williamson, O. E. (1985). *The economic institutions of capitalism: Firms, markets, relational contracting*. New York, NY: Free Press.
- Williamson, O. E. (1991). “Comparative economic organization: The analysis of discrete structural alternatives”. *Administrative Science Quarterly*, 36(2), 269–296.
- Yin, R. K. (2009). *Case study research: Design and methods* (4. ed.). Thousand Oaks, Calif.: Sage.

ENVIRONMENTAL, ECONOMIC AND FINANCIAL UNCERTAINTIES OF NUCLEAR ELECTRICITY

Patrizia Ghisellini^{*1}, Cosimo Rota¹ and Sergio Ulgiati²

¹ *Alma Mater Studiorum - University of Bologna, Department of Protection and Valorization of Agriculture and Food, Section of Economics, Reggio Emilia, Italy*

² *Parthenope University of Napoli, Department of Sciences for the Environment, Napoli, Italy*

ABSTRACT

The so-called nuclear *revival* worldwide is investigated for environmental impact, technical feasibility, nuclear fuel availability, market competition, financial risk and macroeconomic impacts. The resulting picture, based on a review of more than one hundred LCA literature studies worldwide points out the existence of a large uncertainty on all the main aspects of the nuclear energy system, thus preventing the policy maker from relying on a stable and certain set of feasibility indicators. Uncertainty therefore becomes the driving concept in decision making about nuclear energy.

Keywords: nuclear energy, energy prices, uncertainty

1. INTRODUCTION. THE NUCLEAR RENAISSANCE.

The first years of the new millennium seem characterized by a renewed interest in nuclear energy (Adamantiades and Kessides, 2009), the so called “nuclear revival” (Owen, 2006). In developing countries thirty plants are in construction against the five in OECD countries (two in Europe: France and Finland) (ARPA, 2009; WNA, 2009). The Italian energy policy is also influenced by this interest wave, after the nuclear phase-out decided in 1987. This resurgence of interest is mainly based on claims that nuclear energy is cheaper, has lower price volatility compared to fossil fuels, it is secure in supply (Linares and Conchado, 2009) and does not contribute to climate change.

1.1 The search for carbon free energy

Low nuclear GHG emissions is perhaps the most emphasized, studied and debated aspect. According to Sovacool (2008a), advocates of nuclear power consider it “the only non-greenhouse gas emitting energy source that can effectively replace fossil fuels and satisfy global demand”. A 1000 MW_{el} coal power plant releases about 6 millions tons of CO₂ per year, while nuclear is claimed by its supporters to be quite CO₂ free. According to the international Nuclear Energy Agency (NEA, 2002) in the last 40 years nuclear has contributed to avoid 1,200 million tons per year of carbon dioxide. Opponents have objected that “nuclear plants are poor substitutes to other less intensive greenhouse gas generators”: wind and hydroelectricity have respectively one-third and one-fourth less CO₂-equivalent emissions than nuclear power. The Oxford Research Group (Sovacool, 2008a) predicts that, assuming constant nuclear capacity, 2050 nuclear CO₂ emissions per kWh would equal those from gas fired power plants due to decreasing uranium ore grade.

* Corresponding author; Telephone number: +39-333-5794792; E-mail address: patrizia.ghisellini@unibo.it

1.2 Radioactive waste

The contribution to climate change is only a part of the story. Other relevant aspects include “high capital cost, proliferation of dangerous materials, nuclear terrorism, operation safety and radioactive waste disposal” (Toth and Rogner, 2006; Romerio, 2007; IAEA, 2008; Lenzen, 2010). Large amounts of nuclear waste have been accumulated in USA (Lior, 2006; Lenzen, 2010) and worldwide and there is no easy solution for radioactive waste disposal or destruction (Lior, 2008). No country has yet adopted a successful disposal after fifty years of nuclear civil programs. The first commercial geological repository is expected to open in Sweden by 2018 (ARPA, 2009); the solution to the nuclear waste issue (short-term and long-term nuclear waste management and spent fuel processing) is a prerequisite for further expansion of nuclear industry (Abu-Khader, 2009).

1.3 Market uncertainty

The actual competitiveness of nuclear must be analyzed in a wider perspective. It cannot only rely on the analysis of greenhouse gas emissions, since nuclear is a very complex and expensive technology and many more aspects come into play. The liberalization of electricity markets shows that the fate of nuclear is strongly affected by energy market structure. The loss of some main favorable conditions (governmental support, certainty of demand, a price regime based on recovering the production cost increase by charging higher prices to consumers, etc), lead to a drop of the number of nuclear plants built from 1990 to 2005 to only 1.7 nuclear plants per year (mainly in developing countries) compared to 17 nuclear plants per year built in the period 1970-1990 (ARPA, 2009). In liberalized electricity markets decisions about energy technologies are driven by the expected returns, taking into account the risks (afforded by the company, rather than by consumers as in a monopoly regime) linked to costs and revenues (Gross et al., 2009). Moreover, nuclear energy has to face new competitors such as renewable source technologies, characterized by a lower carbon content, better environmental footprint, increased population acceptance and higher growth rates favoured by cost reduction driven by technological innovation.

2. NUCLEAR ENERGY. A WORLD OVERVIEW

About 440 reactors are presently in operation in 30 countries with a total installed capacity of 372 GW_{el}. Compared to fossil fuels, used in power generation, residential, commercial, industrial and transport sectors, nuclear energy is only used for electricity generation. Electricity from all sources has a market share of about 17.1% worldwide and 21.1% in OECD countries, in terms of final energy consumption. The nuclear share of world electricity supply during the period 1973-2008 increased from 3.3% (1973) to about 18% (1990), then decreased to 13.5% (2008) (De Paoli, 2008; IEA, 2010). Oil powered electricity declined its share from 24.7% (1973) to 5.5% (2008). Natural gas and to a lesser extent coal expanded their share in the same period (IEA, 2010).

Nuclear energy supplies about 34% of the total electricity produced in the European Union. Italy does not have nuclear plants in operation but imports about 15% of its electricity mainly from France, where 77% of electricity comes instead from nuclear (ENEA, 2009). The global nuclear electricity generation (except for China and India) is projected to increase at rates lower than the overall electricity generation by 2030 (Lenzen, 2010). IEA (2008) foresees an installed capacity increase to 415-519 GW_{el} in 2030, EIA (2010) predicts an increase to 481 GW_{el}, and OECD-NEA projections predict up to 600 GW_{el} (Lenzen, 2010). Such a lower growth rate can be attributed to public concerns about safety, proliferation risks, restrictions in supply chains due to skilled labor shortage and insufficient enrichment capacity, lack of experienced contractors, lack of solutions for spent fuel disposal. According to Lenzen (2010) promises of performance

improvement (higher resources sustainability, inherent safety, substantial reductions in radioactive waste volumes and lifetime) rely on the new generation-IV reactor and fuel cycle technology, foreseen by 2030.

2.1 Uranium market: a gap between demand and supply

The annual world uranium production has been around 50,772 t_U in 2009 covering about the 77.5% of annual demand (that is around 65,500 t_U) (WNA, 2010a). The gap between demand and production has been (and still is) met by secondary sources such as low enriched uranium (LEU) from the dismantling of nuclear warheads, re-enrichment of depleted uranium tails and spent fuel reprocessing (NEA, 2010). Two main periods of high uranium exploration can be identified. The first one, in the 1950s, was driven by the demand of weapon industry while the second one, in the 1970s, was due to the fast development of nuclear civil programs as a reaction to the 1973 oil embargo (Remme et al., 2007). Prices have been recently rising after about twenty years of decreasing trend (WNA, 2010a), thus stimulating new exploration activities and leading to an increased resource supply (Lenzen, 2010). World uranium Reasonably Assured Resources (RAR) and inferred resources were 3.2 Mt_U in 2003, increasing to 4.7 Mt_U in 2005, 5.5 Mt_U in 2007 (Lenzen, 2010) and finally 6.3 Mt_U in 2009 (D'Urso, 2010). RAR and inferred resources should provide uranium for the next 100 years at current production rates (Lenzen, 2010). Mudd and Diesendorf (2008) highlight that, despite perceived resource scarcity, the last two nuclear programs (nuclear weapon race in the 1940s and civil nuclear development in the 1960s) have been followed by new resource discovery. As with all fossil fuels, it is expected that the new deposits explored in the future will be deeper compared to most of the presently exploited deposits. The average ore grade mined is also expected to be lower as far as the best deposits are exploited, although Canadian newly discovered deposits show an increasing trend (Mudd and Diesendorf, 2008; Heinberg, 2009).

2.2 A “peak” for uranium?

The gap between demand and supply of uranium raises concerns for a possible peak of world uranium. Compared to oil, uranium is relatively abundant but difficult to find at economically attractive concentration grades. The trend of production and the increase in price are signals of the gradual depletion of the best deposits and the need for exploiting new deposits that could require higher investments and extraction costs. Uranium is having the same trend as oil, where scarcity and increasing extraction costs are causing the so-called “oil peak”. Some authors suggest that uranium is also near to or has already passed its peak (Bardi, 2006; Heinberg, 2009), although this trend is not easy to be confirmed because of the irregular production activities. The future of nuclear power will be heavily affected by either the scarcity of uranium resources and the increase of extraction costs, so that it might be difficult to keep the promises of cheap nuclear energy.

3. THE NUCLEAR FUEL CYCLE

Nuclear electricity is the final product of several upstream activities from mining to processing and finally converting the nuclear fuel. These activities, together with downstream disposal and processing of used fuel, constitute the nuclear fuel cycle (WNA, 2010b). A fuel cycle can, in turn, be classified into two types: “once-through” (open) and “closed”. The latter types “reuse the nuclear materials extracted from irradiated fuel” (IAEA, 2009) while the former ones do not reuse nuclear materials and discharge them directly into disposal sites (Sovacool, 2008a). The choice between “open” or “closed” cycles is an important national policy decision (IAEA, 2009). At present most of the nuclear reactors operate adopting the “once-through” cycle (Owen, 2006; Sovacool, 2008a). Reactors operating with closed cycles, separate waste products from the still

fissionable material, that is reprocessed and re-used. The reprocessing activity has the double advantage to reduce both the upstream demand for natural uranium and the downstream waste that must be disposed of (Lenzen, 2008; Sovacool, 2008a). Closed-cycle reactors have however disadvantages linked to the reprocessing costs, proliferation risks and problems with fuel cycle safety (Sovacool, 2008a).

3.1 The five steps of nuclear cycle

The two nuclear cycle types share at least five interconnected stages: (1) upstream or “front-end” activities, in which uranium is extracted from ore (open pit, underground mining or in situ leaching), milled, converted to uranium hexafluoride, enriched and finally used to make the fuel element; (2) power plant construction; (3) plant operation and maintenance; (4) downstream or “back-end” activities, in which the spent fuel is conditioned, reprocessed and disposed in final repositories (if any); (5) plant decommissioning and mine site reclamation (Sovacool, 2008a). Other related activities (heavy water and zirconium alloy production) and transport of the materials among the different steps must also be taken into account (Owen, 2006; IAEA, 2009).

4. ENVIRONMENTAL ANALYSIS OF NUCLEAR ENERGY FUEL CYCLE

We reviewed 9 LCA studies published since 2000, dealing with the nuclear fuel cycle at a different level of detail and scope. Four of them are actual LCAs of specific cycles (Lee *et al.*, 2000, 2002; Dones *et al.*, 2005; Wissel and Spohn, 2008), while the other five are in turn reviews of the existing literature (Gagnon *et al.*, 2002; Fthenakis and Kim, 2007; Sovacool, 2008a; Lenzen, 2008; Fthenakis and Kim, 2009), making up for more than one hundred of cases compared and summarized.

4.1 Main focus on greenhouse gases

Most of the reviewed studies are focused on greenhouse gas emissions over the nuclear fuel cycle (Lenzen, 2008; Sovacool, 2008a) or on the comparison with other fossil or renewable energy cycles (Gagnon *et al.*, 2002; Dones *et al.*, 2005; Fthenakis and Kim, 2007). The latter also include indicators different than greenhouse gas emission, such as radioactive emissions (noble gases, H₂, C¹⁴, aerosols, Actinides; Dones *et al.*, 2005); SO₂, and NO_x emissions, and direct land requirements (Gagnon *et al.*, 2002; Fthenakis and Kim, 2009), indirect land requirements (Fthenakis and Kim, 2009), energy payback ratio (Gagnon *et al.*, 2002; Lenzen, 2008), and energy requirements (Lenzen, 2008).

4.2 Comparing CO₂ emissions from nuclear with other electricity generation processes

A comparison of the average CO₂ emissions from different types of power plants powered by either renewable and nonrenewable sources (Table 1) shows a very large range of options, with nuclear ranking low compared to fossil fuels and still high compared with wind, hydro and other renewables. The most surprising aspect in the reviewed studies is the large spread of estimates of CO₂ emissions from nuclear. Sovacool (2008a) calculates an average emission of 66 g CO₂/kWh_{el}, but due to the spread based on very different assumptions the real meaning of such an average is questionable and therefore scarcely useful for nuclear policy planning.

4.3 Dealing with uncertainty

Some authors (Fthenakis and Kim, 2007; Sovacool, 2008a; Lenzen, 2008) investigated the causes that contribute to the uncertainty of LCA estimates about nuclear GHG emissions in the literature. For Sovacool (2008a) the main reasons are: scope (e.g.

some studies do not include all the stages of fuel cycle); assumptions about the quality of uranium ore (decreasing uranium grade in ore increases GHG emissions, as the lower the grade of uranium ore the higher the quantity of rock to be extracted and handled, the higher the energy needed and the GHG released); type of mining (methods of extraction and source of energy used for the extraction; for example uranium extracted closer to industrial centers releases less GHG emissions than the one extracted from mines in remote areas that rely on less efficient sources of energy); enrichment method (diffusion method is an older technology that requires much more energy than the centrifuge one); spatial focus (some studies assess emissions from specific reactors while others assess national and global average emissions based on industry data (individual cases in general provide a variety of estimates, while an average emissions approach always provides higher estimates); measurement of historical or marginal/future emissions (some of the studies refer to historical emissions while others look at future emissions for some type of plants, e.g. Dones et al., 2005); reactor type (the different design of reactor affects the GHG emissions: CANDU is considered by many as one the most GHG efficient commercial reactors); site selection (the location is a factor that in many ways affects a reactor's GHG performance; for example Canadian nuclear life cycles are associated to less GHGs than Chinese ones); operational lifetime (lifetimes and capacity factors vary in the reviewed studies yielding different estimates); the LCA applied (economic input-output based LCA, process-based LCA, and hybrid LCA have been applied, generating different GHG emission estimates; according to Fthenakis and Kim, 2007, the first method gives emissions 10-20 times higher than the process-based one). Lenzen (2008) identifies ore grade and enrichment method as the main factors that affect the energy and GHG performances in LWRs (also depending on the energy mix of the country), while only the ore grade affects HWRs, since the latter do not require enriched uranium. Fthenakis and Kim (2007) highlight enrichment, production and operation stages.

Table 1. CO₂ emissions from different typologies of power plant

Technology/fuel	Power/typology	Emissions range (gCO ₂ /kWh _{el})
Wind	2.5 MW, offshore - 1.5 MW onshore	9-10
Hydroelectric	3.1 MW, reservoir - 85 MW reservoir	10-12
Solar thermal	80 MW, parabolic	13
Biomass (short rotation forest and waste wood)	Co-combustion with hard coal- steam turbine-reciprocating engine	14-41
Solar PV	CdTe-Polycrystalline silicon-CIS	19-70
Geothermal	80 MW, hot dry rock	38
Nuclear	300/1600 MW/Various reactor types	1-290
Natural gas	300-700 MW/Various combined cycle turbines	398-450
Geothermal	20 MW, hot water/wet steam field	380-650
Hydrogen from nat gas reforming	Fuel cells (stand alone or hybrid with gas turbine)	493-664
Diesel and Heavy oil	320 to 1280 MW/Various generators and turbine types	778-923
Coal	320 to 1280 MW/Various generators and turbine types	960-1100

Source: after Brown and Ulgiati, 2002; Dones *et al*, 2005; Fthenakis and Kim, 2007; Lenzen, 2008; Wissel and Spohn, 2008; Sovacool, 2008a; Ulgiati et al, 2010.

4.4 Looking out of the “global warming” boundaries

The potentialities of an LCA are related to the possibility to identify the most environmentally significant stages as well as the process contribution to more than one impact category. Providing a global picture of the environmental impacts, not only GHG emissions, is very important for transparent information to the society. In particular, out of the 9 studies reviewed, only Lee et al. (2000) and Lee and Koh (2002) carried out an LCA

purposefully with these objectives as well as “to solve the problem when LCA is applied to facility releasing the radioactive wastes” (Lee et al., 2000). Their results show that the nuclear fuel cycle causes important environmental impacts also in other impact categories. Lee et al. (2000) included in the study the upstream activities, the nuclear power plant, the waste treatment (once-through cycle) and all transportation steps. The functional unit was the delivery of 1 GWh of electricity from 11 PWRs in commercial operation in 1998 in Korea. The authors found that the main environmental impacts caused by nuclear fuel cycle were abiotic depletion (73.3 g/yr), human toxicity through air (40.9 g-body Wt/yr) and global warming (27.7 g-CO₂/yr). They also identified mining and milling as the dominant stages in the cycle. These steps contribute to the largest depletion of abiotic resources (ADP) (96%), ecotoxicity through aquatic pattern (ECA) (98%) and human ecotoxicity through water (HCW) (78%). Lee and Koh (2002) applied LCA to three different nuclear cycle alternatives (once-through fuel cycle, with direct use of PWR spent fuel in CANDU reactor (DUPIC process) and recycling with plutonium and uranium recovery (PUREX process). The latter option resulted to be the less environmental loading. Internal exposure was identified as the most radiologically significant step.

Fthenakis and Kim (2009) focused on the life-cycle direct and indirect land use, measured as land transformation and land occupation, respectively for conventional and renewable sources. According to these authors, the electricity generation pattern that is less demanding in terms of land is nuclear (120-150 m²/GWh_{el}), followed by coal (depending on the typology of mining: 100-900 m²/GWh_{el}), photovoltaics (land demand 164-600 m²/GWh_{el}, with potential of much better values in case of rooftop PV), natural gas (260 m²/GWh_{el}), wind electricity (1000-2000 m²/GWh_{el}), and finally biomass (12500 m²/GWh_{el}). Gagnon *et al* (2002) estimated direct land use for renewables (hydro with reservoir, hydro run-of-river, biomass plantation, sawmill wastes, solar photovoltaic, wind power), coal cycles and nuclear. For nuclear they presented two values: without/with the land needed for the long-term waste. In the first case they estimated a value of 5000 m²/GWh_{el}, a much higher value compared to other sources. In the second case the direct land requirement for nuclear increased to 100000 m²/GWh_{el} (assuming that: “0.1 km²/Wh_{el} is required for waste disposal, multiplied by 30,000 years, applied to 30 years of generation”).

4.5 Lack of standardized procedures, lack of consensus

It clearly appears that the different assumptions, perceptions of Authors and evaluation methods heavily affect the final results in many ways, by providing different estimates or by disregarding some steps or impact categories. In spite of the standardized LCA procedure called for by ISO 14040/2006 and ISO 14044/2006 norms, with clear requirements about boundaries, procedures, and impact categories, a large uncertainty is introduced into the set of results by a kind of reluctance to compare on the same basis. In so doing, in spite of the large number of studies performed and reviewed, consensus about impacts is far from being achieved.

5. ECONOMIC AND FINANCIAL RISKS OF NUCLEAR POWER

Within the context of liberalization of worldwide electricity market the evaluation of investments plays a central role to complement the scientific debate (Holgner and Langlois, 2000; Adamantiades and Kessides, 2009; Linares and Conchado, 2009). Two economic and financial methodologies are adopted to this purpose: the consolidated Net Present Value (Rothwell, 1997, 2003; Greenpeace 2008) and the Real Option Value, considered more suitable for decision making in high and dynamic uncertainty contexts (Pindyck, 1993; Dixit and Pindyck, 1994; Holt et al. 2010). In both cases, risk analysis is one of the key tools to judge nuclear competitiveness as an investment option.

From a strictly economic point of view three main risk factors are considered: (a) construction time, (b) investment costs and (c) variability of operating costs. Most of the

existing plants have been built under a monopolistic regime, with governmental guarantees and controlled market prices, low capital costs and low investment risk (Owen, 2006). The investment risk, and the capital cost increased with deregulation of energy markets and were charged to electrical companies, penalizing capital intensive investments projects with long time return on investment and low technological flexibility (Romerio, 2007). Instead, investments in alternative power sources, be they combined cycle gas turbine plants and smaller renewable plants have been favored (Zorzoli, 2005). In such a context, investments on nuclear sector became uncertain and very variable. Considering a medium size nuclear plant (1000-1600 MW), construction costs are up to 10 or 15 times higher than those required for the construction of a natural gas plant (100-700 MW) per MW installed (Clò, 2008). The projected costs also tend to increase due to the extension of construction time (cost overruns) (Linares and Conchado, 2009). Finally, costs for nuclear plants decommissioning are estimated as about 25% of the original investment costs. The total costs of a nuclear plant can be splitted into about 60-75% *fixed* costs (capital repayments, interest allowed, decommissioning costs) and 25-40% *variable* costs (for instance, the cost of uranium and labor) (Owen, 2006). Unlike gas and carbon plants, the share of nuclear fuel cost on total production costs is small (Owen, 2006; Lenzen, 2010). This is due to two factors: 1) the amount of uranium still available, capable to satisfy the present nuclear industry requirements (demand); 2) the nuclear reactor capability to store the uranium for a long time (Owen, 2006). As the fuel cost is low companies in OECD countries are trying to capitalize this advantage extending reactor working life. While the cost of electricity obtained from nuclear energy is not particularly affected by fluctuations of raw material price, other uncertainty factors related to security aspects, licensing, escalation of decommissioning costs (De Paoli, 2008), radioactive wastes disposal, might contribute to increase the financial risk perceived from private investors and, consequently, the level of expected return (Lenzen, 2010). The risks associated to the construction of a new nuclear plant reduce the international rating of the companies involved. Moody's suggests that after beginning the construction the downgrade risk increases sensitively (Moody's 2009). Therefore if a company is on category "A" before the plant construction, it could be downgraded to the "Baa" category (neither highly protected nor poorly secured) during the following 5-10 years, when the construction costs reach the peak and the main credit parameters are (lower) or negative. In this situation, within an inefficient credit market, it could be more difficult for the company to obtain further credit, while instead the interest rate and, consequently, the cost per kWh_{el} are likely to increase. Some authors (Sovacool, 2008b; Lazard, 2009; MIT, 2009;) calculated the levelized cost of nuclear electricity production, which is an international indicator of the average costs of electricity produced by a plant in one year. Linares and Conchado (2009) provide details of the shortcomings of this indicator in deregulated markets. Such a methodological approach takes into account *internal* costs (implementation, maintenance, fuel and operating costs) and *external* costs, both rather uncertain (De Paoli, 2008). According to a recent study (MIT, 2009) the levelized cost of nuclear electricity is 8.4 \$ cent/kWh_{el}, higher than the costs of coal (6.2 \$ cent/kWh_{el}) and gas powered electricity (6.5 \$ cent/kWh_{el}). Lazard (2009) provides higher estimates (nuclear electricity between 9.8-12.6 \$ cent/kWh_{el}, coal electricity between 7.4-13.5\$ cent/kWh_{el} and solar termal power between 9-10.4 \$ cent/kWh_{el}, and even higher costs for natural gas, biomass and wind power). Rogner and Langlois (2000) highlight that the future of nuclear power depends on the competitiveness strategies that industries, supported by technological innovation, will adopt to guarantee the economic and financial sustainability and reduce the safety risks. Such targets require strong political support to the nuclear industry. For instance, the problems related to waste disposal and safety involve suitable technological solutions and communication, able to achieve social consensus. Therefore, an energy policy which includes the use of nuclear power among its energy sources will have to handle three problems: overcoming the scarcity of public funds, choosing the best nuclear technology available, and finally conducting a cost-benefit analysis to compare nuclear with others renewable sources (Linares and

Conchado, 2009). As a consequence, a macroeconomic analysis to evaluate these aspects in the light of the above listed risks is an unavoidable step.

6. ANALYSIS OF THE MACROECONOMICS EFFECTS OF A NUCLEAR PROGRAM

After the 1973 oil crisis many oil-importing countries developed strategies to reduce their dependence on fossil fuels also by implementing suitable energy alternatives (Toth and Rogner, 2006; Romerio, 2007). The new energy policy “paradigm” translated into plans for increased share of nuclear electricity. Such a paradigm was challenged by the antinuclear opposition and destabilized by the technical and economic problems encountered by the nuclear sector itself, although the Kyoto protocol has also indirectly contributed to reconsider the nuclear option (Romerio, 2007). Governmental intervention in support of nuclear is perceived by industrial sectors and analysts as a policy to achieve energy security and therefore a public good. In fact “it may be argued that market imperfections would lead to an underprovision of energy security”. Supply security can be analyzed qualitatively through the identification of the external and internal factors that can undermine it, their possible effects and the tools of mitigation as well as the possible indicators that give information about the level of energy security.

6.1 The case of nuclear energy in U.K.

Watson and Scott (2009) investigated the supply security in UK and the role of new nuclear plants in addressing it. They identified four factor (internal and external) that can affect supply security:

1) Fossil fuel scarcity and external disruption: fossil fuel availability has affected the economies of oil importing countries (and some exporting ones) through rapidly rising prices (there are a few cases of supply shortages after a sudden price increase). The development of nuclear or renewable sources or even demand reduction are believed to be able to mitigate these negative effects (Awerbuck and Sauter, 2005). The role of nuclear needs to be compared with gas-fired generation, as it is the most likely investment option for large scale power generation.

2) Lack of domestic investment in infrastructure: nuclear can contribute in UK to replace the power generation capacity needs foreseen over the next two decades, but its long implementation time compared to gas-fired generation should also be considered. The lack of investment in infrastructure to generate and supply energy to customers likely leads to price variability and possible disruptions too. Moreover, the UK's renewable commitment by 2020 (UK-DECC, 2009) affects nuclear plans, as they are both base load power, not flexible in responding to short-term peaks in demand. Additional measures to develop flexible plants as well as capacity of storage and demand management are required in order to increase the resilience of the energy system.

3) Technology and infrastructure failure: this type of threat can lead to serious problems to local and international populations (as in the case of Three Mile Island and Chernobyl accidents). Problems may also arise from scarce technology diversification in the power system (e.g. class failures of new generation gas turbines in the 1990s, malfunctioning of nuclear plants in France because of the intense heat in summer 2003).

4) Domestic activism or terrorism: it can be challenged by reactor design which can incorporate protection systems to several risks but they are very costly (Watson and Scott, 2009). These authors conclude that U.K. nuclear would contribute to mitigate negative effects of supply security problems (such as fossil fuel price increase and scarce technological diversification), in particular in a scenario of replacement and expansion of electricity capacity but its role could lead to the increase of other types of risk.

Kennedy (2007) investigated UK costs (predevelopment, construction, operation and maintenance, fuel supply, waste disposal, decommissioning and cost of capital) and benefits (environmental benefits and security supply) of new nuclear compared to gas-fired generation, on-shore and off-shore wind, coal CCS (retrofit and new), and marine.

The welfare balance of new nuclear for the different scenarios hypothesized (assuming different nuclear, gas and carbon prices) is negative at low gas prices/high nuclear costs across the ranges of CO₂ prices and positive in case of central gas price depending on the CO₂ price and in high gas price/low nuclear cost case across the range of CO₂ prices (including a zero CO₂ price). According to Kennedy (2007), nuclear generation could have an advantage in a political framework characterized by a continued commitment to carbon emission reduction and the presence of steadily increasing gas prices.

7. CONCLUSION

The picture that results from our review of more than one hundred studies worldwide is a rather *uncertain* scenario about the majority of aspects of nuclear energy development. The future availability of suitable grade uranium is uncertain. Nuclear development scenarios seem to be associated to higher costs and prices than in the past. Shortages in the nuclear supply chain as well as the indefinite state of spent fuel worldwide could create additional barriers. Significant *uncertainties* are also linked to environmental impacts (uncertain GHG emission estimates, scarce knowledge of the contribution to other impact categories); to financial analysis (nuclear investment in competitive market is penalized compared to renewable sources and gas-fired generation, as it is characterized by high capital costs, long time return on investment and low flexibility; these factors contribute to increase the financial and economic risk for investors) as well as to macroeconomic analysis (it is uncertain the role that nuclear could have in addressing energy security; since gas-fired generation is the major competitor of nuclear in a cost-benefit perspective, the potential benefit of new nuclear is strongly affected by gas prices, carbon prices and nuclear costs).

In the presence of such large and diverse uncertainties, a wise policy is not just "learning by doing", nor even relying on expected "innovation" or "science results". Choices may generate conflicts among equally legitimate interests, which calls for participatory decision-making and planning. Once further and more reliable information is made available, the usual top-down decision-making process must be converted into a participatory procedure that involves all the stake-holders and the affected communities. In particular, when "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1991), the concept itself of "feasibility" must be converted from "technical and economical feasibility" into a more complex framework that includes aspects of "post-normal" science, namely the shift from the expert community to an "extended peer community" consisting of all those affected by an impact who are ready to enter into dialogue on it. They bring in alternate points of view, that include local knowledge and expertise not generally accounted for in normal scientific reports as the ones reviewed in this paper. It is not, therefore, a "to-do" list that should emerge out of such studies, but instead a call for multicriteria strategies and the awareness of the need for more complex evaluation tools and participatory planning.

REFERENCES

- Abu-Khader M., M., 2009. Recent advances in nuclear power: a review. *Progress in Nuclear Energy*, 51: 225-235.
- Adamantiades A., Kessides I., 2009. Nuclear power for sustainable development: current status and future prospects. *Energy Policy*, 37: 5149-5166.
- ARPA, 2009. Agenzia Regionale Prevenzione ambiente dell'Emilia Romagna. Ritorno al nucleare, reale convenienza o illusione?
http://www.arpa.emr.it/cms3/documenti/_cerca_doc/ar05_09nucleare.pdf.
- Awerbuch S., Sauter R., 2005. Exploiting the oil-GDP effect to support renewables. University of Sussex. Sussex, UK.
- Bardi U., 26 settembre 2006, Uranio e petrolio. Picchi in parallelo?
http://www.scanziamolescorie.org/index2.php?option=com_content&do_pdf=1&id=74

- Clò A., 2008. Il rebus energetico. Tra politica, economia e ambiente. Il Mulino, Bologna.
- De Paoli, G., 2008. Prospettive e problemi dell'energia nucleare nel Mondo. <http://www.svilupposostenibile.org/documenti/10 - DE PAOLI.pdf>
- Dixit A. K., Pindyck R. S., 1994, *Investment under uncertainty*, Princeton University Press, Princeton, N.J.,
- Dones R., Heck T., Emmenegger M., F., Jungbluth N., 2005. Life Cycle inventories for the nuclear and natural gas energy systems, and examples of uncertainty analysis. *Ecoinvent. Energy Supply, Int J. LCA* 10 (1): 10-23.
- EIA, 2010. U.S. Energy Information Administration. Electricity, International Energy Outlook. <http://www.eia.doe.gov/oiaf/ieo/electricity.html>
- ENEA, 2009. Rapporto Energia e Ambiente 2008. Analisi e scenari; www.enea.it.
- Fthenakis V., M., and Kim H., C., 2007. Greenhouse-gas Emissions from solar electric and Nuclear Power: A life-cycle study. *Energy Policy*, 35: 2549-2557.
- Fthenakis V., M., and Kim H., C., 2009. Land use and electricity generation: a life-cycle analysis. *Renewable and Sustainable Energy Reviews*, 13: 1465-1474.
- Gagnon L., Bélanger C., Uchiyama Y., 2002. Life-cycle assessment of electricity generation options: the status of research in year 2001. *Energy Policy*, 30: 1267-1278.
- Greenpeace, 2008. Uncertainty and high economic risk: the net present value of an investment in nuclear power.
- Gross R., Blyth W., 2009 Heptonstall P., (Article in Press). Risk, revenues and investment in electricity generation: why policy needs to look beyond costs. *Energy Economics*:1-9.
- Heinberg R., 2009. Searching for a miracle. A Joint Project of International Forum on Globalization and Post-Carbon Institute.
- Holt L., Sotkiewicz P., Berg S., 2010. Nuclear Power Expansion: thinking about uncertainty. *The Electricity Journal*, Volume 23, issue 5: 26-33.
- IAEA, 2009. International Atomic Energy Agency. Nuclear fuel cycle information system; http://www-pub.iaea.org/MTCD/publications/PDF/te_1613_web.pdf
- IEA, 2008. International Energy Agency. World energy outlook. <http://www.iea.org/textbase/nppdf/free/2008/weo2008.pdf>
- IEA, 2010. International Energy Agency, Key World Energy Statistics. http://www.iea.org/textbase/nppdf/free/2010/key_stats_2010.pdf
- Kennedy, D., 2007. New nuclear power generation in the UK: cost benefit analysis. *Energy Policy*, 35: 3701-3716.
- Lazard, 2009. Levelized Cost of Energy Analysis - Version 3.0. New York, NY: Lazard Ltd. [Full-text at <http://bit.ly/agFmJA>]
- Lee Y., E., Lee K., J., Lee B., W., 2000. Environmental Assessment of nuclear power generation in Korea. *Progress in Nuclear Energy*. Vol. 37, No. 1-4:113-118.
- Lee Y., E., Koh K.,-K., 2002. Decision-making of nuclear energy policy: application of environmental management tool to nuclear fuel cycle. *Energy Policy*, 30: 1151-1161.
- Lenzen M., 2008. Life Cycle energy and greenhouse gas emissions of nuclear energy: a review. *Energy Conversion & Management*. 49, 2178-2199.
- Lenzen M., 2010. Current state of development of electricity-generating technologies: a literature review. *Energies* 2010, 3: 462-591.
- Linares P., Conchado A., 17 agosto, 2009. The economics of new nuclear power plants in liberalized markets. Università Pontifica Comillas. <http://www.iit.upcomillas.es/pedrol/documents/economicsnuclear.pdf>
- Massachusetts Institute of Technology (MIT), 2009. Update of the MIT 2003, Future of Nuclear Power; <http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf>.
- Moody's Global Infrastructure finance, June 2009. New Nuclear generation: rating pressure increasing. http://www.nukefreetexas.org/downloads/Moodys_June_2009.pdf
- Mudd G., M., Diesendorf M., 2008. Sustainability of uranium mining and milling: toward quantifying resources and eco-efficiency. *Environmental Science & Technology*, 42: 2624-2630.
- NEA, 2002. Nuclear Energy Agency. Organisation for Economic Co-operation and Development: Nuclear Energy and the Kyoto Protocol: <http://www.nea.fr/ndd/reports/2002/nea3808-kyoto.pdf>
- NEA, 2010. Nuclear Energy Agency. <http://www.nea.fr/pub/newsletter/2010/28-1/NEA-News-28-1.pdf>
- Owen A., 2006. Nuclear power for Australia?. *Agenda*. Volume 13, (3): 195-210.
- Pindyck R. S., 1993. Investments of uncertain cost, *Journal of financial economics*, Vol. 34, 53-76

- Remme U., Blesl M., Fahl U., 2007. Global resource and energy trade: An overview for coal, natural gas, oil and uranium. Institute of energy economics and the rationale use of energy. University of Stuttgart.
- Rogner H.,-H., Langlois L., 2000. The economic future of nuclear power in competitive markets. International Atomic Energy Agency (IAEA). Vienna, Austria.
- Romerio F., 2007. Nuclear energy between past and future. An assessment based on the concept of risk. Competition and Regulation in Network Industries. Volume 2, No. 1.
- Rothwell G., S., 1997. Continued operation or closure: the net present value of nuclear power plants. The Electricity Journal. Volume 10, issue 7: 41-48.
- Rothwell, G., S., 2003. Nuclear power economics (Academic press/Elsevier science).
- Sovacool, B.K., 2008a. Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy, 36: 2940-2953.
- Sovacool, B.K., 2008b. Renewable energy: politically sound, politically difficult. Volume 21, issue 5: 18-29.
- Toth, B.F.L. and Rogner, H.H., 2006, Oil and nuclear power: Past, present, and future. Energy Economics, 28: 1-25.
- UK-DECC, 2009. Departement of energy and climate change, UK renewable energy strategy. http://www.decc.gov.uk/assets/decc/What%20we%20do/UK%20energy%20supply/Energy%20mix/Renewable%20energy/Renewable%20Energy%20Strategy/1_20090717120647_e_@_TheUKRenewableEnergyStrategy2009.pdf
- Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Federici, M., Franzese, P.P., Raugeri, M., Viglia, S., Zucaro, A., 2010. Multi-Method and Multi-Scale Analysis of Energy and Resource Conversion and Use. In: F. Barbir and S. Ulgiati (Eds), Energy Options Impact on Regional Security. Springer Science + Business Media, Dordrecht. Pp. 1-36.
- Watson J., Scott A., 2009. New nuclear power in the UK: A strategy for energy security? Energy Policy, 37: 5094-5104.
- Wissel S., Mayer-Spohn O., 20-26 September 2008. CO2 emissions of nuclear electricity generation. Institute of energy economics and the rationale use of energy. University of Stuttgart. IYNC 2008, Interlaken Switzerland.
- WNA, 2009. World Nuclear Association. The nuclear renaissance. <http://www.world-nuclear.org/info/inf104.html>
- WNA, 2010a. World Nuclear Association. Uranium markets. <http://www.world-nuclear.org/info/inf22.html>
- WNA, 2010b. World Nuclear Association. The nuclear fuel cycle. <http://www.world-nuclear.org/info/inf03.html>
- Zorzoli G. B., 2005. Il mercato elettrico dal monopolio alla concorrenza. Franco Muzzio Editore, Roma.

THE EFFECTS OF USING DIFFERENT MIXES OF ENERGY SOURCES IN THE GENERATION OF ELECTRICITY IN EUROPE

X. Gabarrell^{*1,3}, E. Amat¹, J. Oliver Solà^{1,2}, C. M. Gasol^{1,2}, & J. Rieradevall^{1,3}

¹ *SosteniPrA (UAB-IRTA). Institute of Environmental Science and Technology (ICTA). Universitat Autònoma de Barcelona (UAB). School of Engineering (ETSE), Campus de la UAB, Bellaterra (Cerdanyola del Vallès) 08193 Barcelona, Catalonia, Spain*

² *Inèdit Innovació S.L. UAB Research Park, Catalonia, Spain*

³ *Department of Chemical Engineering. Universitat Autònoma de Barcelona (UAB), Catalonia, Spain.*

ABSTRACT

The aim of this presentation is to show that the market and the political strategy can determine the environmental behaviour of a theoretically optimum electricity mix (20% of renewable according to European Union target). In order to demonstrate that, it is carried out an evaluation of the environmental impact of the electricity produced in Spain comparing days with different levels of renewable electricity production and special demand restrictions. In a previous study it was carried out a macro analysis of the energy mix in two European countries: Belgium and Spain. The methodology chosen for the micro analysis as well as the macro is the Life Cycle Assessment (LCA), described in the international standard series ISO 14040-43. The functional unit has been defined as the production of 1 kW h of electricity.

There exist several environmental assessments of electrical technologies, as well as some energy scenarios for near and far future in different European countries. These studies show important benefits in terms of reduced environmental impacts for renewable technologies compared to other competing electricity generation technologies, especially in terms of emissions of greenhouse gases; however few of them deal with the barriers of the electrical market rules. Renewable technologies are available. However, if they are not accompanied by the appropriate policy strategies and measures to reduce the total electricity demand, those technologies will not be able to have a significant contribution in any electricity mix.

This study enlarges the current body of knowledge by relating the market rules of the Spanish electricity system with the environmental impacts of electricity production for different days with extreme variation on renewable generation. The environmental impacts are compared by source, trying to demonstrate the potential benefits of renewable technology and that it would be necessary to establish policies to regulate the electricity market in terms of environmental benefits instead of monetary benefits. Moreover, carrying out an analysis of the electrical system at micro level allows studying the consequences of electricity mix variations due to seasonal demand.

In a previous study we had analyzed the impacts on the environment of different energy mixes at present and in the future for Belgium and Spain, also by performing a LCA (Foidart et al., 2010). Those countries had been elected as, even if both are members of the European Community with common targets for 2020, they present very different electricity markets, renewable energy sources (RES-E) deployment opportunities and also political strategies. LCA was carried for the 2005 electricity mix as well as for several possible referenced scenarios to reach EU and also national legal objectives at the horizon 2020 and 2030; assumption that consumption would decrease by 20% compared to initial 2020 projections thanks to campaigns and behavioural changes were only considered in the most optimistic scenarios. Then, results showed that ambitious renewable energy sources' deployment plans can decrease significantly impacts on the environment as RES-E replace polluting traditional sources, such as coal/lignite, oil or gas. Indeed, when concentrating, for example, on global warming, one of the main impact category in this type of study, the performed Life Cycle Impact Analysis (including mid-point impact analysis) indicated that in 2005, the emissions of CO₂ equivalent ranged from a 0.32 kg per KWh electricity produced in Belgium to 0.54

* Corresponding author; E-mail: xavier.gabarrell@uab.cat

kg in Spain; this significant difference was justified by the higher share of coal and oil in the Spanish electricity mix, even if limited in relative value (respectively 29% and 7%). Those energy sources can jeopardize effort made on RES-E deployment as in Spain at the same time, it was already significant (representing 16% of the total production). However, when concentrating on future projections, it was obvious that a mix with a combination of less coal and oil replaced by much more RES-E energy sources would bring environmental benefits for Spain, where such scenarios show CO₂ emissions equivalent around 0.2 kg per KWh. In Belgium, the trend was at the opposite as whatever scenarios, they would include more coal and gas without much more RES-E, it would become more environmental harmful (up to 0.56 kg per KWh produced in the 2030 scenario including the nuclear phase-out).

INTRODUCTION

The electricity mix is defined as the combination and proportion of technologies used to provide electric energy at any given time and place. This contribution is, according to the technology availability and requirements, mainly determined by the policy strategy adopted by each government and for by the rules of the electricity market itself. One crucial characteristic of electricity is that it cannot be stored in large amounts. Therefore production must always keep a constant instantaneous balance between production and consumption (demand). In these terms, the role of a system operator it is crucial for maintaining the equilibrium between the different power stations according to the type of technologies and their features.

In Spain, the electricity mix in 2008 was 32% combined cycle (natural gas), 20% nuclear, 16% coal, 11% wind power, 9% hydropower and the rest of technologies contribute less than 1.5% each one (see table 1 for more detailed data).

Table 1. Spanish gross energy production 2008 (Source: REE, 2008)

Sources	MWh	%
Coal	46.274.877	15,98%
Natural gas	115.612.766,8	39,92%
Industrial gas	452.000	0,16%
Hydropower	26.157.408	9,03%
Nuclear	58.973.422	20,36%
Photovoltaic	2.245.524	0,78%
Wind power	31.111.728	10,74%
Cogeneration biomass	2.472.114	0,85%
Cogeneration biogas	3.398.246	1,17%
Incineration	2.897.383	1,00%
Total	289.595.469	100,00%

Spanish electricity market rules

The Spanish electricity market gives freedom of contract to producers, marketers and consumers, as established by Law 54/1997 and its subsequent amendments (currently the Law 17/2007), in accordance with EU regulations on the internal electricity market. According to this principle, opportunities for participation in the electricity market are either long-term bilateral contracts or contracts traded on the daily market which is set to the Iberian market (Spain and Portugal).

The electricity operator Operador del Mercado Ibérico de Energía (OMEL) is responsible for managing the daily and intra-day markets. The technical management of the system is entrusted to the Spanish electricity system operator, REE. The role of a system operator consists on maintaining the balance and, for this purpose, it forecasts consumption and operates and oversees the generating and transmission installations in real time. Thus ensuring that production planned at the power stations coincides at all times with the instant consumer demand. If a difference arises between the two, it sends the appropriate instructions to the power stations to increase or reduce their output.

In the daily market, the electricity producers make deals to sell certain quantities of electricity at a certain price, for each of the hour. At the same time, consumers, directly or indirectly through the electric companies make offers to purchase. To meet this demand, the cheapest offer supply is chosen. However, until the complete liberalization of the market, scheduled for the 1st of July 2009, electricity prices for small consumers are set by the administration.

The result guarantees that the maximum capacity of interconnection to external electrical systems considering physical bilateral contracts involving international interconnections is not exceeded. Once the daily market session ends, the system operator assesses the technical feasibility of the production units to ensure safety and reliability of supply in the transport network. If the result of the daily market and bilateral contracts fails in respect to the physical capacity for exchanges between electrical systems, or safety requirements, the procedure for resolving technical restrictions is as follows: first, it changes the purchases or sales from external electrical systems causing the excess exchange interconnection; second, it changes the allocation of energy production units. There is also an intraday market used to make adjustments. The complementary services and the management of deviations aim that the supply of electrical energy is produced in the conditions of quality, reliability and security that are established and that the generation-demand balance is verified permanently.

In this context, it is clear that any environmental criterion is taken into account when managing the electricity system. Only in the construction phase of the power stations and of the distribution and transport system the potential environmental impact is taken into account, since it is required by law (Decree 1/2008 for which the text of the Environmental Impact Assessment Law is approved) to carry out an environmental impact assessment of the project. Therefore, during the operation of the electric system any other environmental impact is internalized in the price.

If environmental costs were internalized renewable energies would increase their participation in the electricity mix, not only to achieve the targets set by post-Kyoto agreements (EU Climate action and renewable energy package) but also because it would be competitive in the electricity market.

Environmental impacts of existing and possible future energy mixes in two EU countries, namely Belgium and Spain

Foidart (Foidart et al, 2010) analysed the environmental impacts of existing and possible future energy mixes in two EU countries, namely Belgium and Spain. As a general remark, it needed to be emphasized that there were temporal and geographical variability as data were coming from different sources (different countries and different years). Projections data used for Belgium were those published by a national body using complex modeling tools (PRIMES model developed by ICCS/NTUA, and HERMES model amongst others) to take into account lots of variables while for Spain, the data were extrapolated from the paper 'Scenarios for the evolution of the Spanish electricity sector: Is it on the right path towards sustainability?'(Linares et al. 2008) using more high-level hypotheses. PRIMES Spanish data exist but could not be utilized, as they do not give sufficient details on the mix of RES-E in the future.

Table 2 shows that in Belgium, over years, the situation would be worsening in all cases, even though at a lower path in the case of the scenario 2020 20/20. This is mainly due to the increase in the production to respond to the growing demand but also to the choice in the electricity mix (no ambitious RES-E deployment scheduled so far). The categories with the highest increase are fresh water and marine eco-toxicity (due to incineration) as well as eutrophication.

Table 2. Characterization results for 1 KWh – Belgium (Foidart et al, 2010)

Impact category	Unit	2005 results per kwh	2020 baseline results per kwh	Changes in % (vs 2005)	2020 2020 results per Kwh	Changes in % (vs 2005)	2030	Changes in % (vs 2005)
Abiotic depletion	kg Sb eq	2,18E-03	3,08E-03	40,90	2,55E-03	16,89	3,97E-03	81,99
Acidification	kg SO2 eq	1,00E-03	1,33E-03	32,67	1,03E-03	2,35	1,47E-03	46,19
Eutrophication	kg PO4--- eq	9,37E-05	1,51E-04	61,54	1,59E-04	69,87	1,63E-04	73,54
Global warming (GWP100)	kg CO2 eq	3,20E-01	4,41E-01	37,86	3,91E-01	22,43	5,63E-01	76,14
Ozone layer depletion (OD)	kg CFC-11 e	2,08E-08	2,07E-08	-0,61	1,95E-08	-6,24	2,19E-08	4,92
Human toxicity	kg 1,4-DB eq	6,56E-02	9,27E-02	41,40	1,01E-01	53,82	1,13E-01	72,43
Fresh water aquatic ecotox	kg 1,4-DB eq	4,21E-02	1,05E-01	148,50	1,59E-01	276,52	9,03E-02	114,34
Marine aquatic ecotoxicity	kg 1,4-DB eq	3,87E+01	6,95E+01	79,90	8,67E+01	124,32	7,27E+01	88,11
Terrestrial ecotoxicity	kg 1,4-DB eq	3,08E-04	4,29E-04	39,33	3,80E-04	23,39	4,63E-04	50,35
Photochemical oxidation	kg C2H4	4,17E-05	5,34E-05	28,14	4,23E-05	1,52	6,21E-05	48,95

In general, whatever the period, electricity generation per capita is always lower in Spain than in Belgium, even though in the baseline scenario the estimation is showing an increase by nearly 30% compared to 2005 situation (from 6196 KWh per capita in 2005 to 9240 KWh in 2020 BAU). Despite the lower per capita consumption, the Spanish situation in 2005 had a bigger environmental impact than the Belgian one. However, over years, with the change in the electricity mix, it should improve significantly, at the opposite of Belgium.

Table 3. Characterization results per capita – Spain (Foidart et al, 2010)

Impact category	Unit	2005 results per KWh	2020 BAU per KWh	% increase per KWh (vs 2005)	2020 PS1 per KWh	% increase (vs 2005)	2020 PS2 per KWh	% increase (versus 2005)	2020 PSAu per KWh	% increase (versus 2005)
Abiotic depletion	kg Sb eq	4,05E-03	2,97E-03	-26,82	2,27E-03	-44,06	1,45E-03	-64,16	1,85E-03	-54,47
Acidification	kg SO2 eq	4,93E-03	1,05E-03	-78,62	6,97E-04	-85,86	6,08E-04	-87,66	6,00E-04	-87,84
Eutrophication	kg PO4--- e	2,48E-04	8,28E-05	-66,61	6,64E-05	-73,23	5,34E-05	-78,45	5,84E-05	-76,46
Global warming (GWP)	kg CO2 eq	5,42E-01	3,70E-01	-31,78	2,81E-01	-48,11	1,84E-01	-66,06	2,31E-01	-57,42
Ozone layer depletion	kg CFC-11 e	2,98E-08	4,09E-08	37,25	3,14E-08	5,31	2,08E-08	-30,30	2,50E-08	-16,08
Human toxicity	kg 1,4-DB e	9,38E-02	5,32E-02	-43,29	4,96E-02	-47,12	4,88E-02	-48,02	5,15E-02	-45,12
Fresh water aquatic ec	kg 1,4-DB e	3,30E-02	8,03E-03	-75,66	7,46E-03	-77,40	8,25E-03	-75,00	7,78E-03	-76,43
Marine aquatic ecotoxi	kg 1,4-DB e	8,72E+01	2,54E+01	-70,85	1,93E+01	-77,91	1,65E+01	-81,03	1,69E+01	-80,59
Terrestrial ecotoxicity	kg 1,4-DB e	1,00E-03	2,77E-04	-72,38	2,18E-04	-78,24	2,06E-04	-79,50	2,05E-04	-79,56
Photochemical oxidatio	kg C2H4	1,83E-04	5,02E-05	-72,51	3,41E-05	-81,31	2,79E-05	-84,70	2,94E-05	-83,87

In both countries, the 2 impact categories presenting the highest per capita equivalent units are marine eco-toxicity (because of incineration as explained before but also to coal and lignite) and global warming.

Comparing the two countries, we can notice that:

- Acidification impact was very high in Spain in 2005 mainly due to coal and lignite; in absolute value, those energy sources were 10 times higher in Spain than in Belgium (80000 GWh in Spain versus 8282 GWh in Belgium). Other sources do not present such high impact (except maybe for oil in Spain: 19000 GWh consumed versus 1824 GWh in Belgium for the same period).
- In 2005, in Belgium, human toxicity is more impacted by gas, oil and biomass while in Spain, it is the result of a high share for coal and gas.
- In 2020 and even more in 2030, the situation would become worth in Belgium mainly due to the use of gas and incineration while in Spain, it would improve thanks to the use of RES-E.

- In 2005, in Belgium, human toxicity was more impacted by gas, oil and biomass while in Spain, it was more due to the use of coal and gas.
- The level of PO₄ eq. (eutrophication) emitted in Spain in 2005 was by far the highest compared to other scenarios, mainly due to the importance of coal in the electricity production. However, the situation in Spain should improve in all other scenarios while in Belgium, it would become worth, due to increasing part of coal but also incineration.
- Gas is the most polluting component for the ozone layer depletion. In 2005, oil in Spain and nuclear in Belgium were also important. In the future, the quantity of CFC-11 emitted in Spain would be more important than in Belgium whatever the scenario because of the relative importance of gas in the mix.

For the global warming impact category (table 4), results indicate that according to the different scenarios, CO₂ emissions per capita in Belgium could more than double over the next 25 years (from 2704 kg CO₂ equivalent produced in 2005 to 6057.42 kg in 2030). In 2020, it could be partially contained if the scenarios 2020 20/20 is applied (at a level of 3899 kg). It is mainly the result of the increasing use of coal and gas in the electricity mix.

Table 4. Impact category 'Global Warming' – evolution per capita and per KWh over years (Foidart et al, 2010)

Scenarios	Per capita (kg CO ₂ eq.)	Per capita (% vs 2005)	Per KWh (% vs 2005)
Belgium 2005	2703.86		
Belgium – 2020 Baseline	4586.88	69.64	37.86
Belgium – 2020 2020	3898.74	44.19	22.42
Belgium – 2030	6057.42	124.02	76.13
Spain – 2005	3359.57		
Spain – 2020 Business as usual	3417.83	1.73	-31.78
Spain – 2020 PS1	2241.74	-33.27	-48.11
Spain – 2020 PS2	1263.26	-62.40	-66.06
Spain – 2020 PSAu	1585.05	-52.82	-57.42

If we refer to the per capita results, the situation could be worth as the total energy demand per capita is supposed to increase over years (from 2703 kg CO₂ equivalent per capita in 2005 to 5230 kg in the 2030 scenario).

After that, to ascertain that the market and the political strategy can condition the environmental behaviour of a theoretically optimum mix (20% of renewable) data from the electricity system of Spain is assessed.

Even though renewable sources are available and technologically feasible, the rules of the electricity market itself make their contribution to the total mix smaller than what the installed capacity would allow.

METHODOLOGY

The methodology used to evaluate the behaviour of the Spanish electricity market is the Life Cycle Assessment (LCA), which is a method for systematic analysis of environmental performance from a cradle to a grave perspective. This analytic tool describes and assesses all flows that enter into the studied systems from nature and all those flows that go out from the systems to nature, all over the life cycle.

A LCA study according to the ISO14040 guidelines follows four steps: (i) definition of the goal and scope of the study; (ii) life cycle inventory (LCI) phase: collection of all the environmental inflows and outflows; (iii) life cycle impact assessment (LCIA) phase; and (iv) interpretation of the results.

The LCI is performed using the software tool SIMAPRO 7.1 by Pré Consultants. In the LCIA the impact assessment CML 2 Baseline 2000 (Guinée, 2002) was selected.

LCA of Spanish electricity system

Goal and Scope definition

The goal of this study is to demonstrate that the market and the political strategy of a country or region condition the environmental behaviour of its electricity mix. The geographic reference used to carry out this assessment is Spain, and the time reference is the year 2008, even though for the future scenario projections reference data is from 2005.

Functional unit

The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables comparison of different systems. In this study, the functional unit used is 1 kWh put into the grid.

Systems description

The systems description of each energy technology used for the study were taken from Ecoinvent v2.0 database (Frischknecht, 2004). In this sense, the system boundaries determined by Ecoinvent take into account the infrastructure construction and decommissioning, the mining exploitation, the production processes, the transport and distribution of materials, the energy carriers, the complete power plant operation, the waste treatment processes for production wastes and the end of life wastes and air pollutants.

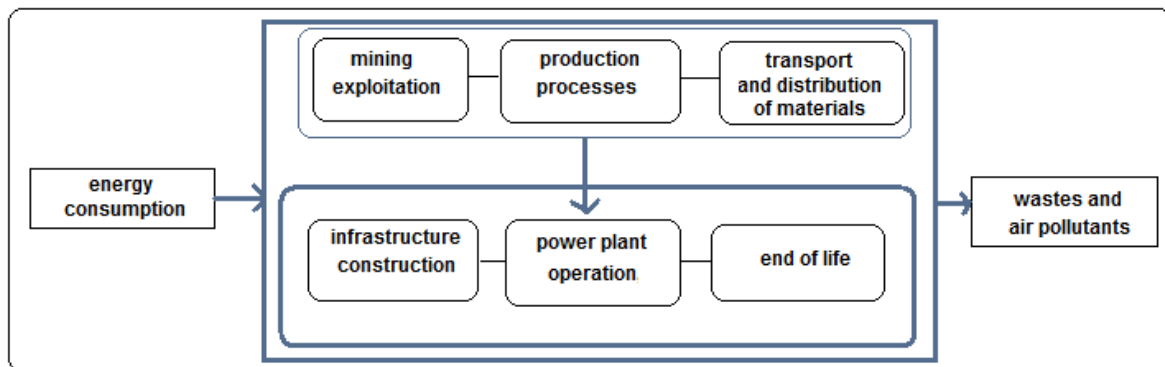


Figure 1. System boundaries for each energy production technology

Life cycle inventory methodology

The methods used in the life cycle inventory phase were mainly focused on the adaptation of data from the different sources to Ecoinvent processes.

The technologies considered within the Ordinary Regime are coal (hard coal and lignite), nuclear, fuel/gas, large hydro and combined cycles; whereas within the Special Regime are considered those electricity generation facilities with an installed capacity not exceeding 50 MW which use renewable energy sources such as wind, solar, mini-hydro (<10MW), biomass and biofuel; urban and industrial solid waste; or any type of cogeneration (forms of electricity production associated with non-electric generation). Special Regime producers may choose between two types of sale: regulated tariff or free market (market price plus premium).

It is important to note that electricity demand has to be met by the internal generation capacity plus (or minus) any international exchanges and the consumption in the generation facilities. In this study international exchanges are not taken into account because of two reasons, first we are analysing only the production impacts and second, they are quite insignificant: in 2008 international exchanges accounted for a minus 4%

(exports) of the total Spanish energy system balance while losses (both generation, pumping and transport losses) represented a 5% from the total generation.

Special-days inventory

For the daily analysis, we chose several single days which accomplished the previously defined requirement: they all implied a non-usual electricity system operation. Therefore, we selected two days with low wind power production, two days with high wind power production, two days of low electricity demand, and two days of high electricity demand. There were also considered two specific days which were remarkable for a singular event: on the 2nd of November 2008 the wind power generation was ordered to stop and on the 26th of May 2009 three nuclear reactors, Ascó I, Ascó II and Vandellòs (aprox. 3.000MW) stopped due to security reasons. Taking two days for each special case was representative enough to state that the system followed the same logic and that the result obtained was not an outlier result.

Table 5. Spanish energy mix as a function of environmental and special demand conditions (% variation compared to the daily average for 2008)

	WINDY	WIND Y	NON WINDY	NON WINDY	MIN DEMAND	MIN DEMAND	MAX DEMAND	MAX DEMAND	Wind power stopped	Nuclear plant stopped
TOTAL	7	-16	13	11	-19	-22	19	16	-18	-7
Hard coal	-26	16	19	9	-46	6	42	39	6	-28
Hydropower power plant	35	-22	15	18	-31	8	12	39	-24	17
Hydropower pumped power plant	-20	39	26	-12	-36	6	33	62	105	-19
Lignite	-25	-32	10	6	-17	16	-1	3	-14	-57
Natural gas	-1	-46	36	31	-34	-61	7	-10	-42	10
Industrial gas	0	0	0	0	0	0	0	0	0	0
Nuclear	-31	-3	-1	-9	13	14	-2	-1	-18	-47
Photovoltaic	0	0	0	0	0	0	0	0	0	0
Wind power	141	47	-46	-26	7	-22	106	114	44	28
Cogeneration biomass	0	0	0	0	0	0	0	0	0	0
Cogeneration biogas	0	0	0	0	0	0	0	0	0	0
Incineration	0	0	0	0	0	0	0	0	0	0

Table 5 shows the variation (%) in the energy mix for the chosen special days compared with the value of the daily average of 2008. Those technologies with no variation (equal to zero) show that their value has been extrapolated to the daily average. As commented before, CNE only provided the annual amount for Special Regime technologies.

We call *windy-days* those days in which the electricity generation from wind power plants was higher than the annual average; in the selected cases, 141% and 47% higher. Accordingly, as *non-windy days* we selected two days in which the production of wind power electricity was especially low.

In general, those days of the year which have a lower energy demand, are related to either summer or Christmas holidays. Therefore, we take the 15th of August 2008 and the 25th December 2008 to implement our analysis which had a distribution demand (Equation 1) of 579.100MWh and 569.197MWh respectively. On average, the daily distribution demand is of 720.812MWh.

Equation 1.

$$\text{Demand} = \text{Production} - \text{Generation losses} - \text{Transport losses} \pm \text{international exchanges}$$

Those days with maximum demand are usually winter days. According to this, we selected two days of December 2008, the 3rd and the 15th which had a distribution demand of 844.370 MWh and 839.383 MWh respectively.

Other special days were, on one hand when wind power production was stopped due to a exceed of production (*REE* ordered to lower the generation to avoid possible incidents on the system) and, on the other, when three nuclear plants (Ascó I, Ascó II and Vandellós II, 1,000 MWe each one) were stopped for security reasons because an error was detected when the tasks of maintenance and fuel load were being carried out.

The impact categories used are: abiotic depletion; global warming; ozone layer depletion; human toxicity; fresh water aquatic ecotoxicity; marine aquatic ecotoxicity; terrestrial ecotoxicity; photochemical oxidation; acidification and eutrophication (excessive nutrients in an freshwater ecosystem). However, this study is focused mainly in the global warming impact since one of the goals of this study is to see if the target of 20% reduction of GHG emissions for 2020 can be achieved (one of the priorities of the EU environmental and energy policies).

Table 6. Impact results for the electricity mix in Spain 2008 (total amount of emissions on each impact category for 1kWh of electricity produced)

Impact category	Unit	Total
Abiotic depletion	kg Sb eq	3.05E-03
Acidification	kg SO ₂ eq	3.20E-03
Eutrophication	kg PO ₄ eq	1.55E-04
Global warming	kg CO ₂ eq	4.19E-01
Ozone layer depletion	kg CFC-11 eq	2.91E-08
Human toxicity	kg 1,4-DB eq	7.56E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	1.08E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	8.68E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	4.00E-04
Photochemical oxidation	kg C ₂ H ₄	1.27E-04

RESULTS AND DISCUSSION

Table 7 shows, for all the scenarios (special days), the impact variation for each category comparing with the 2008 annual balance values (showed in table 6). The comparison of the results obtained for the different special days helps to evaluate which could be a more sustainable energy mix in terms of environmental impact.

Table 7. Impact variation (%) compared with the 2008 annual balance

	Windy		Non-windy		Min demand		Max demand		Wind Stop	Nuclear Stop
Abiotic depletion	-17,45	-9,90	12,23	9,08	-20,18	-11,67	-1,92	-7,32	-5,32	-2,86
Acidification	-29,21	3,85	0,59	-2,38	-12,93	39,35	-2,29	1,01	14,73	-37,78
Eutrophication	-21,20	11,71	3,00	-0,32	-12,83	19,58	-0,40	0,70	13,60	-12,19
Global warming	-17,86	-7,13	9,85	6,91	-17,23	-5,85	-3,24	-7,10	-2,38	-4,27
Ozone layer depletion	-12,16	-26,06	14,85	12,46	-10,92	-34,44	-10,79	-19,48	-21,63	8,67
Human toxicity	-8,59	8,51	-1,27	-2,37	-4,30	10,47	-0,53	0,67	11,66	-4,94
Fresh water aquatic ecotox.	-12,54	19,00	-8,31	-9,07	13,53	31,88	-15,29	-6,31	21,56	1,36
Marine aquatic ecotoxicity	-19,39	11,19	-2,71	-4,67	-1,00	30,52	-7,46	-2,35	16,67	-14,98
Terrestrial ecotoxicity	-19,10	19,68	0,44	-2,60	-14,93	26,55	6,92	8,55	20,19	-17,43
Photochemical oxidation	-27,73	0,53	1,33	-1,38	-12,37	34,26	-3,54	-0,95	11,81	-34,91

The most extreme variations are those related to the acidification category. On a day with high contribution of wind power or with a decrease of nuclear generation, the acidification impact decreases by approximately 30%. This is due to the fact that the nuclear decrease is compensated by wind energy production which is not associated with processes such as acid precipitation and acidic runoff.

For the global warming impact category, the values which show a better scenario are both the windy and the min demand, with a variation, in both cases, of about 17% from the average value. This result has two different explanations. On the first case, on a windy day, the contribution of natural gas is substituted by the wind power generation which has no CO₂ emissions since it does not imply any combustion process. On the other, in a day of minimum demand the use of natural gas decreases from 40% (2008 annual balance) to less than 20%, while the contribution of nuclear increases substantially (from 20% to 30%). This can be due to either a market offer-demand curve or due to the lack of wind intensity to provide a bigger amount of energy generated with this source.

When the day is more favourable to an entrance of renewable energy, there is no such entry insured, either for economic reasons, or for technological viability related to resources availability (e.g. climate conditions such as solar radiation or wind force). However, when the case is the contrary, when there is enough wind intensity to really increment its contribution to the system, allowing a reduction of energy from fossil fuels (which in fact are the ones that have a higher environmental impact), for some reason this situation is not exploited and even some renewable plants are ordered to stop. And, unfortunately, the resulting environmental impacts are therefore the same than in a day in which there had been no wind.

Global warming emissions produced by 1kWh electricity generated (taking into account all the life cycle) on each analyzed day vary according to the contribution of the different technologies to the electric mix. Values are around 400 g CO₂ eq/kWh, and most of them come from the natural gas and coal contribution, and in much less proportion from municipal waste incineration (Table 8).

Table 8. Global Warming impact (kg CO₂ eq / kWh)

Special days	kg CO ₂ eq / kWh
Windy day	0.34
Windy day	0.39
Non windy day	0.46
Non windy day	0.45
Min demand	0.35
Min demand	0.39
Max demand	0.41
Max demand	0.39
Wind power stop	0.41
Nuclear stop	0.40
2008 Balance	0.42

The analysis of the Spanish electricity system carried out in this study allows to see how the market behaves in some particular cases and to what extent environment impacts are related to changes in the electricity mix.

It is clear that there is a direct relation impact-contribution, in other words, in those scenarios where a technology has more contribution, it is more responsible for the related impacts. However, it is also undeniable that there are some technologies which are more harmful than others, and policy-makers should act according to this information. The Spanish electricity sector is presently mainly governed by market rules without taking into account the environmental impacts that each technology has. Moreover, it has a very high energy dependence (not because it is importing electricity but the sources to generate it, e.g. coal, gas, uranium and others) and a critical volume of CO₂ emissions.

In conclusion at the macro level, increasing the part of RES-E in the electricity mix will not ensure an improvement on the environment conditions if governments do not put in place integrated policies. The examples of those two countries show that it is important to play on the demand side by reducing energy consumption as well as on the supply side by an extending RES-E deployment. As a major conclusion at the micro level, and although it does not examine individual demand-side policy measures, our quantitative analysis shows that the key strategy towards a less environmental impacting scenario would be to set a regulation framework which forced, on favourable days, the incorporation into the system of the electricity production from renewable origin thus, following environmental criteria and not only economic. Otherwise, it should be mandatory for electricity producers to internalize into their costs the environmental impacts mitigation associated with the generation technology used, as it is done for the GHG emissions market. This would encourage the use of renewable energy allowing to meet the EU targets for the 2020.

Further studies are needed in this direction, attempting to estimate what should be the price to pay for compensating the environmental impacts caused by each technology in order to find the equilibrium point in the curve of supply-demand but once internalized the environmental costs associated (including not only those that have been mentioned in this study but also those related to other impacts such as radioactivity). Probably the result of those studies would be show such a huge price that it would be worth to encourage the use of already existing renewable technologies and promoting research and promotion of new technologies (thermo solar, geothermal, etc.) rather than internalizing those costs.

REFERENCES

- F. Foidart, J. Oliver-Solá, C.M. Gasol, X. Gabarrell, J. Rieradevall. "How important are current energy mix choices on future sustainability? Case study: BELGIUM & SPAIN - Projections towards 2020-2030" *Energy Policy*, Volume 38, Issue 9, September 2010, Pages 5028-5037
- Frischknecht R., Jungbluth N., editors, 2004. *Ecoinvent project*. Swiss Centre for Life Cycle Inventories, Dübendorf, Switzerland. Available from: www.ecoinvent.ch
- Guinée, J.B., 2002. *Handbook on Life Cycle Assessment. Operational Guide to the ISO standards*, Dordrecht.
- Linares P., Santos F.J., Pérez-Arriaga I.J. "Scenarios for the evolution of the Spanish electricity sector: Is it on the right path towards sustainability?" *Energy Policy*. Vol. 36, n. 11, pp. 4057-4068. 2008a.
- OMEL. *Mercado de electricidad. Memoria del 2007*.
- REE. *El sistema eléctrico español. Avance informe 2008*.

SESSION 2.3

INTEGRATING ENERGY SYSTEMS WITH NATURAL PROCESSES

Gaudreau K., Gibson R. B., Fraser R. A.

INTEGRATED SUSTAINABILITY AND SYSTEMS ASSESSMENT APPLIED TO
SMALL-SCALE BIODIESEL IN BARBADOS

Agostinho F. and Ortega E.

INTEGRATED FOOD, ENERGY AND ENVIRONMENTAL SERVICES
PRODUCTION AS AN ALTERNATIVE FOR SMALL RURAL PROPERTIES IN
BRAZIL

Siciliano G.

THE SOCIO-ECONOMIC AND BIOPHYSICAL DIMENSIONS OF
URBANIZATION STRATEGIES IN RURAL CHINA: LAND USE CHANGES,
HUMAN TIME AND ENERGY INTENSITY

Buonocore E., Franzese P. P., Ulgiati S.

ALTERNATIVE ENERGY SOURCES: INTEGRATING URBAN WASTEWATER
TREATMENT AND WOOD BIOMASS PRODUCTION FOR BIOENERGY
PURPOSE

Carrasquer B., Martínez A. and Uche J.

AN ANALYSIS OF TECHNICAL ALTERNATIVES IN A WASTEWATER
TREATMENT PLANT BY USING SLUDGE AS ENERGY RESOURCE

Foran B.

LOW CARBON TRANSITION OPTIONS FOR AUSTRALIA

INTEGRATED SUSTAINABILITY AND SYSTEMS ASSESSMENT APPLIED TO SMALL-SCALE BIODIESEL IN BARBADOS

Kyrke Gaudreau^{*1}, Robert B. Gibson¹, Roydon A. Fraser²

¹ *Environment and Resource Studies – University of Waterloo, Waterloo, Canada*

² *Mechanical and Mechatronics Engineering, University of Waterloo, Waterloo, Canada*

ABSTRACT

This paper poses the question: How do we assess energy sustainability for small-scale projects? Many forms of energy assessment are currently available, but most are either not sufficiently comprehensive to cover necessary criteria for sustainability, or not appropriate for use for assessing small-scale endeavours. To this end, the authors propose a modest energy assessment methodology based upon sustainability assessment, but supplemented by the insights of complex systems thinking: notably resilience, and energetics. This paper offers a novel articulation of complex systems theories at a smaller scale of analysis than they are normally applied, and addresses tensions between different approaches to sustainability and complex systems thinking. To illustrate the approach, the methodology is used post-facto to assess a small-scale biodiesel plant in the Caribbean. The results of the analysis indicate that for the specific context at hand, the main benefit of small-scale biodiesel production is in promoting social learning, and societal transformation, rather than enhancing energy security and waste management, or replacing the energy infrastructure of Barbados. While the conclusions are drawn for a biodiesel operation in a specific context, the underlying principles may be generalized beyond.

Keywords: sustainability assessment, resilience, energetics, complex systems thinking

1. INTRODUCTION

Energy sustainability is an important issue at all scales and in all locations, and one that is receiving much attention due to concerns over climate change, energy supply, and the socio-ecological impacts of energy consumption. There are currently many different approaches to assessing the sustainability of energy systems, such as net energy analysis (Hagens and Mulder 2008), emergy (Odum 1996), multi-criteria analysis (Buchholz, Rametsteiner et al. 2009), multi-scale integrated assessments (Giampietro and Mayumi 2000), and sustainability assessments (Gaudreau and Gibson 2010; Winfield, Gibson et al. 2010). Some of the assessments are rooted within the ontology of normal science, while others have a decidedly post-normal (vis-a-vis Funtowicz and Ravetz 1993) basis to them. The approaches all ask different questions. None of the approaches is perfect, and none is necessarily ideal for all contexts and scales.

This paper develops a modest proposal for assessing energy sustainability at the small scale. Assessments of small-scale endeavours have the particular challenge of needing to be sufficiently comprehensive, to acknowledge the implications of the endeavour in the larger context, but still be manageable given limited resources and knowledge. To address this problem, the authors propose an approach to assessment that has two core foundations, both of which are rooted in complex systems thinking and post-normal science. The first is a sustainability-resilience assessment approach, which synthesizes insights from Gibson's sustainability assessment (Gibson, Hassan et al. 2005) that focuses on requirements for progress towards sustainability and how the

^{*} Corresponding author; E-mail: kyrke.gaudreau@gmail.com

interrelations of these requirements can be addressed in ways that deliver multiple, mutually reinforcing and lasting gains, with the Resilience Alliance's use of the concept of resilience and the associated properties of a resilient world (Walker and Salt 2006; ResAlliance 2007; ResAlliance 2007). The second foundation is energetics, a field that studies the flows of energy in complex systems (Odum 1996; Giampietro 2004). The synthesis of energetics with sustainability-resilience assessment has not previously been applied in any published work we know of.

To illustrate the application of an integrated sustainability-resilience-energetics (SRE) approach, we have used it to assess a small-scale biodiesel project in the Caribbean. The project was initially assessed using a combined sustainability-resilience framework (the details are presented in Gaudreau and Gibson 2010), with the insights from energetics applied post-facto. For our purposes, the Barbadian biodiesel case has the advantages of being potentially attractive from a sustainability and resilience perspective, broadly similar to countless other initiatives, and small enough to illustrate how a quite modest sustainability based review can serve common project evaluation purposes.

2. METHODOLOGY

As indicated above, the basic methodology illustrated here is two-fold. First, it combines established sets of generic sustainability assessment criteria with key insights from resilience analysis to develop a sustainability-resilience assessment. Second, the results of the sustainability-resilience assessment are interpreted through an energetics framework (via a heart transplant metaphor), to better understand how the proposed (or current) undertaking operates within the broader context of a self-organizing complex system.

Sustainability assessment criteria

The generic sustainability criteria illustrated in Table 1 were developed for a broad range of applications in broadly defined environmental assessments and planning cases. They are meant to cover the full set of key requirements for progress towards sustainability, with emphasis on the interrelations among these requirements and attention to the potential for an upward spiral of positive feedbacks for mutually reinforcing gains. To encourage integrated thinking, the generic categories have been defined to avoid the usual reductionist triple bottom line pillars of sustainability (Gibson, Hassan et al. 2005).

Table 1. The generic sustainability assessment criteria

Socio-ecological system integrity -Build human-ecological relations to establish and maintain the long-term integrity of socio-biophysical systems and protect the irreplaceable life support functions upon which human as well as ecological well-being depends. Livelihood sufficiency and opportunity -Ensure that everyone and every community has enough for a decent life and that everyone has opportunities to seek improvements in ways that do not compromise future generations' possibilities for sufficiency and opportunity. Intragenerational equity - Ensure that sufficiency and effective choices for all are pursued in ways that reduce dangerous gaps in sufficiency and opportunity (and health, security, social recognition, political influence, etc.) between the rich and the poor. Intergenerational equity - Favour present options and actions that are most likely to preserve or enhance the opportunities and capabilities of future generations to live sustainably. Resource maintenance and efficiency - Provide a larger base for ensuring sustainable livelihoods for all while reducing threats to the long term integrity of socio-ecological systems by reducing extractive damage, avoiding waste and cutting overall material and energy use per unit of benefit. Socio-ecological civility and democratic governance - Build the capacity, motivation and

habitual inclination of individuals, communities and other collective decision-making bodies to apply sustainability requirements through more open and better informed deliberations, greater attention to fostering reciprocal awareness and collective responsibility, and more integrated use of administrative, market, customary and personal decision-making practices.

Precaution and adaptation - Respect uncertainty, avoid even poorly understood risks of serious or irreversible damage to the foundations for sustainability, plan to learn, design for surprise, and manage for adaptation.

Immediate and long term integration - Apply all principles of sustainability at once, seeking mutually supportive benefits and multiple gains.

–from (Gibson, Hassan et al. 2005, chapter 5)

These generic sustainability assessment criteria provide a common base for assessment anywhere and on any undertaking, and apply to examination of options and results at all stages of an assessment process from the initial delineation of purposes, through comparative evaluation of alternatives and potential approval options, to implementation and eventual closure or renewal. In all applications, however, specification for case and context is needed. Approaches to such specification have been documented, particularly for a major project review (Gibson 2006) and for evaluation of a proposed provincial scale, electricity sector systems plan (Gibson 2006; Gibson, Winfield et al. 2008), and for the present biodiesel case study (Gaudreau and Gibson 2010). The reader is encouraged to read these articles to better understand how the criteria are elaborated for a specific case.

Resilience criteria

Resilience approaches to social-ecological systems issues commonly faced in environmental assessment emerged largely from the domains of ecological modelling and resource management. Resilience thinking is useful in elucidating system dynamics within and among various scales (Walker, Holling et al. 2004; Walker and Salt 2006). Resilience analysis is still being developed as a methodology, with preliminary forms described in several works including the Resilience Alliance workbooks (ResAlliance 2007; ResAlliance 2007) and the development of the panarchy concept (Gunderson and Holling 2002). Because of their respect for system complexity and uncertainty, advocates of resilience thinking and associated analyses are hesitant to embrace prescriptive approaches that might encourage overconfidence in prediction and management. With this caveat, Walker and Salt (Walker and Salt 2006) identify the nine properties of a resilient world that are presented in the form of criteria in Table 2.

Table 2. Criteria for resilient societies

Diversity - Promote and sustain diversity in all forms (biological, landscape, cultural, social and economic) as a major source of future options and system capacity to response to change and disturbance

Ecological variability - Embrace and work with ecological variability rather than attempting to control it (e.g. to maximize returns)

Modularity - Favour largely self-reliant systems (modules) to avoid over-connectedness and associated relations of dependence, which become vulnerable to shocks

Acknowledge slow variables - Focus on slow controlling variables that configure social/ecological systems and are associated with thresholds

Tight feedbacks - Maintain or strengthen feedbacks that are tight and strong enough to allow detection of thresholds before they are crossed (versus slow or delayed feedbacks with weak signals)

Social capital - Promote trust, well-developed social networks, and responsive leadership, all of which serve adaptability

Innovation - Emphasize learning, experimentation, locally developed rules, and capacity and willingness to shift away from thresholds to undesirable futures or over thresholds to more desirable futures

Overlap in governance - Foster redundancy of institutions, and a mix of governance players and relations and tools (e.g. common and private properties with overlapping access rights) to increase response diversity and flexibility

Ecosystem services - Recognize all ecosystems services, including those currently unpriced (e.g. pollination, water regime maintenance, climate reliability, and nutrient cycling)

– adapted from (Walker and Salt 2006, chapter 6)

These nine criteria are narrower in scope than the sustainability criteria, in part because they do not attempt to identify the desirable qualities of socio-ecological systems beyond the capacity to adapt and persist. The resilience criteria do, however, complement the sustainability-based assessment criteria in several important ways. They clarify the qualities needed for socio-ecological integrity and suggest means of acting on requirements for precaution and adaptation. Moreover, they temper the sustainability criterion for enhanced resource and energy efficiencies by pointing to the need for sufficient system redundancy and for safety cushions between exploitation levels and potential system thresholds.

Integrating and specifying sustainability and resilience criteria

The synthesis of the various approaches is achieved by incorporating resilience criteria into Gibson's sustainability assessment framework. In every application, the particulars of case and context are crucial. Different contexts feature different trajectories, capacities, vulnerabilities, possibilities and preferences; different cases raise different options and face different influences, barriers and openings. An example of the case specific criteria for a sustainability-resilience assessment can be found in Gaudreau and Gibson (2010).

Adding the insights from energetics

Energetics is a relatively broad term to describe research that promotes the understanding of self-organizing systems, and how they process, and rely upon, energy. There are several different energetics approaches to energy assessment, with perhaps the two most famous being energy (Odum 1995; Odum 1996) and multi-scale integrated assessment of societal metabolism (Giampietro and Mayumi 2000; Gomiero and Giampietro 2001). Table 3 lists four key insights from energetics drawn from the work of Giampietro and Mayumi (2009).

Table 3. Key insights from energetics

Energy Return On Investment (EROI) – This is the ratio between the quantity of energy delivered to society by an energy system and the quantity of energy used directly and indirectly in the delivery process. The lower the EROI in a closed cycle, the more the gross energy produced in the conversion process is required simply to produce itself.

Labour productivity – Complex societies are predicated upon a high labour return on investment (notably in the energy and agricultural sectors). The more labour required for supplying surplus energy to society, the less labour is available to maintain the rest of the functioning economy.

Land requirements – For all proposed energy conversion systems, we must ensure that the land requirements are not over-burdening, with an understanding that as the EROI of an energy source decreases, the land requirements will necessarily (if all else remains unchanged) increase in order to maintain a constant power level.

Quality of the energy – The quality of an energy carrier is both an intrinsic characteristic of the

carrier itself (e.g., its exergy) as well as a characteristic of the context in which the energy carrier is consumed.

Power requirements - Complex systems depend upon a source of energy, at a sufficient quality, and supplied at sufficient rate (power), for their survival.

(adapted from Giampietro and Mayumi 2009)

Energetics may be applied as a methodology in and of itself (e.g. Gomiero and Giampietro 2001), or as a set of criteria incorporated within an expanded sustainability-resilience assessment. For the present work, the authors apply energetics via Giampietro and Mayumi's (2009) heart transplant metaphor. According to Giampietro and Mayumi, before changing energy sources one must ensure that the proposed energy source matches both the metabolic characteristics (e.g., energy consumption, power density) and the constraints (e.g., land and labour availability) of society. This replacement of energy sources is metaphorically similar to performing a heart transplant.

The heart transplant metaphor provides a means of exploring the implications of energetics in a qualitative and preliminary manner, which fits the constraints of assessing small-scale projects. However, research is underway to integrate energetics more formally within the sustainability-resilience assessment.

3. SAMPLE APPLICATION – SMALL-SCALE BIODIESEL IN BARBADOS

To illustrate application of the SRE framework, we have applied the heart transplant metaphor to a previous assessment of an existing small-scale biodiesel plant in Barbados. Barbados is a relatively prosperous Caribbean island, but one that faces many challenges. Some of these are rooted in its reliance on and vulnerability to outside forces (from global economic shifts and oil price changes, to changes in tourist behaviour and international steps to discourage tax evasion) over which it has little influence. These considerations suggest needs for further economic diversification, enhancement of self-reliance, conversion to renewable energy sources, and development of more broadly distributed livelihood opportunities. Means of acting on these needs are constrained by the island's limited resources. A large percentage of food is imported (WRI 2006). Barbados suffers from scarcity of water (Sealy 2006), forests (Mongabay 2007), and landfill capacity (Barbados 2004). Finally, Barbados imports a great majority of its fossil fuels (EIA 2009), in part to generate electricity (which is primarily dependent on diesel, fuel oil and natural gas) (BL&P 2009).

The case study biodiesel system is a small-scale biodiesel plant that, at the time of the research, employed three workers (two men and one woman). The plant converted used cooking oil that was collected by pickup truck from a wide range of suppliers (e.g., restaurants, road-side stands, schools, concerned individuals). Biodiesel production was based on first generation thermo-chemical technology that produces biodiesel and glycerin from methanol, used cooking oil and sodium hydroxide using a process known as transesterification. This first generation system is common for small-scale projects (Kemp 2006; Phalakornkule, Petiruksakul et al. 2009).

The case-specific sustainability and resilience criteria

For reasons of brevity, the case specific criteria are not described here; they can be found in (Gaudreau and Gibson 2010). The specification of the combined generic sustainability and resilience criteria for the particular case and context was initiated as a group exercise that included the researchers, interns working at the biodiesel plant, and key stakeholders involved in the biodiesel operation. The sustainability-resilience assessment was undertaken by developing and filling out a sustainability-resilience table, which sets out the most significant particular considerations related to the sustainability-resilience criteria. In practice, the development of the specified criteria set and the completion of the sustainability-resilience assessment table were linked activities, which

proceeded jointly through several iterations of adjustments to table contents involving decisions on what to include where, and with what emphasis and specificity. Key results of the final sustainability-resilience assessment are provided in Table 4. For each consideration, the project's contributions to sustainability are ranked on a 3-point scale, identifying positive impact (+), negative impact (-), and impact that may be either positive or negative depending on how the project is undertaken (=).

Table 4. Key results from the sustainability-resilience assessment

Social-ecological system integrity and resilience	
Dumping or indefinite storage of toxic wastes materials (methanol, glycerin and wastewater) present occupational hazards and local endanger flora, fauna and groundwater.	-
Process has large on-site water requirements (3:1 ratio water to biodiesel) in a water scarce country; partial mitigation through rainwater harvesting during the wet season is possible.	-
Operation reduces landfill pressure by removing oil from waste stream.	+
Product displaces non-renewable diesel fuel, but requires imported methanol at a ratio of 1L methanol for each 5L biodiesel.	+
Main input for biodiesel production is a product of an unhealthy fast food lifestyle.	-
Small-scale production is modular, leading to greater system resilience.	+
Local production innovation, with largely local feedstock and local consumption, establishes visible system links for better understanding and management.	+
Production could be scaled up for greater impact on long term resource availability	+
Initiative adds economic diversity to a tourist-oriented economy.	+
Livelihood sufficiency and opportunity	
Diseconomies of small scale limit financial viability. Long-term success requires subsidization, lower input costs, or a willingness by consumers to pay higher prices.	-
Employment of three people represents far more jobs per litre of production than in larger scale operations, although current low selling price for biodiesel reduces potential for workers to make a decent income.	=
Further employment along the production chain (e.g. refining glycerin into a value added product) is possible, especially if aggregate production increases.	+
There are competing uses for the most desirable waste oil (high quality and/or readily available) including pet food manufacturing and heat generation.	-
Multiple small-scale operations could cooperate to gain some economies of scale.	+
Small scale and ability for multiple configurations improves modularity, and provides potential to produce biodiesel in different contexts and niches.	+
Intragenerational equity	
Both men and women have equal opportunity to produce biodiesel.	+
Scale of operation has low impact on Barbados' fossil fuel dependence.	+
Intergenerational equity	
Biodiesel contributions should help foster a more self-reliant, diverse and lasting energy supply system.	+
Biodiesel is a good transition fuel to facilitate a move from the current fossil based energy system to a variety of potential future renewable systems.	+
Social learning involved in small-scale biodiesel amounts to knowledge development for the next generation.	+
System has low legacy costs because components can be easily disassembled and used for other purposes and wastes are not persistent hazards.	+
Resource maintenance, feedback and efficiency	
Use of waste vegetable oil as the primary input reduces current resource extraction.	+
Product partially displaces non-renewable diesel, although it still requires methanol and uses diesel-based electricity. Importing methanol is not efficient in the long run.	+
Small-scale operation suffers from diseconomies of scale, (e.g., methanol input costs and quality control testing).	-
Small-scale operation could use more energy efficient technologies (e.g., solar heating).	+
Biodiesel has multiple uses, including transport fuel, heating, and electricity generation.	+
Small scale and multiple possible configurations improve modularity and flexibility.	+

Perceived green benefits of biodiesel may rationalize fuel over-consumption, thereby inducing an undesirable feedback (i.e. efficiency paradox).	-
Social-ecological civility, networks and governance	
Operation promotes capacity building through community groups.	+
Process is an excellent education tool to raise understanding of waste reduction, fuel consumption, CO ₂ emissions, and water use issues.	+
On a small close-knit island, a successful small-scale operation can affect government policy positively (e.g. building support for decentralized renewable energy production).	+
Biodiesel encourages broad involvement of diverse participants (e.g. government, farmers, local high school, parish representatives, High Commissions/embassies, restaurants).	+
Precaution and adaptation for resilience	
Project presents low risk of significant damage.	+
Conventional diesel remains as a back-up fuel source.	=
Lack of accurate data for lifecycle assessments adds some uncertainty to the analysis, requiring ongoing research and adaptive management on the part of all stakeholders.	=
Biodiesel production system is flexible enough for physical and operational reorganization, thereby improving resilience.	+
Small-scale encourages interpersonal communication and tight feedbacks.	+
Multiple small-scale biodiesel operations would provide modularity (one could shut down without seriously affecting biodiesel supply) as well as joint savings.	+
Social learning aspects of production may encourage culture of conservation.	+
Interactive effects delivering multiple, mutually reinforcing and lasting benefits	
Operation has mostly positive effects on several linked sectors, including waste management, energy security, local employment and economic diversification.	+
Biodiesel demonstration may promote a transition from imported non-renewable to domestic renewable energy sources, improving resilience and energy security	+
Operation's effects promote social learning in a variety of social-ecological contexts (waste management, energy security, human and ecological health).	+
Without proper government support, biodiesel production may cease on the island.	-

Analysis of the findings

The sustainability-resilience assessment outlined above points to three critical themes – socio-ecological issues, scale issues, and social learning issues – that are not likely to have been revealed so clearly by less broadly framed assessments.

Socio-ecological issues: While renewable energy and waste reduction reasons are often given for promoting biodiesel and biofuels, the analysis above does not indicate that the Barbados biodiesel operation has strongly positive overall socio-ecological system effects. While the biodiesel operation reduces waste oil volumes sent for landfilling (presuming the waste oil would not otherwise go to other competing re-users), and conventional fossil diesel imports to the island, these advantages are compromised by substantial process water requirements in a water scarce country, production of a waste product that is rarely handled properly, and use of electricity from a grid powered by diesel (and other fossil-fuel-based) generators.

Scale issues: Small-scale biodiesel generally has the capacity to be more dynamic and adaptable, and to engage more stakeholders. Other advantages of small scale include increased resilience due to modularity of design; simplicity of operation; the possibility of physical, operational and institutional reorganization; tighter feedbacks among different stakeholders because more stakeholders are operating in the same level; and increased employment per unit biodiesel produced. Unfortunately, there are also diseconomies of small scale. Small-scale producers, each producing independently, cannot afford to produce biodiesel in Barbados at a competitive price in part because of the subsidization of conventional diesel and the current lack of subsidies for biodiesel, but also because of the high unit cost of small volume purchases of methanol. Small producers also often lack proper quality control and manage hazardous materials and

wastes poorly, in part because of the high unit costs of quality control, material handling, and training.

Social learning issues: Biodiesel is not often promoted or examined for its potential to create networks linking different stakeholder groups and to foster social learning. These benefits are visible in a sustainability and resilience analysis in part because the social learning effects of small-scale biodiesel are not related to the biodiesel end product so much as to the larger biodiesel production system. Furthermore, both scale and socio-ecological systems factors are important to the social learning: the systems provide the context for social learning, while the small scale allows for greater networking with tighter feedbacks. For social learning, biodiesel has several advantages. Biodiesel production involves and can link a great diversity of stakeholders (e.g., government, farmers, schools, and restaurants) in a system that raises important national issues, including diet and health, waste and water management, energy security, and economic diversification. As a hub for discussion, biodiesel initiatives can build social awareness of important issues, and also encourage further research into more environmental friendly production techniques. Finally, with gradual scaling up, biodiesel could be a transition fuel, facilitating a shift from the current transportation and energy infrastructure to more sustainable future options.

4. BUT WILL IT WORK? APPLYING ENERGETICS VIA THE HEART TRANSPLANT METAPHOR

The combined sustainability-resilience assessment provided both novel and surprising findings, such as the importance of the social learning issues of small-scale biodiesel. However, the assessment, as such, does not explicitly, nor sufficiently, address the role of the biodiesel operation with regards to being part of the energy supply sector of a metabolic system.

Due to the nature of the specific biodiesel operation collecting used cooking oil, the land requirements for biodiesel production are relatively small. Many small-scale biodiesel producers using waste oil operate out of their sheds (c.f. Kemp 2006), and this plant was similar in this regard. Where land becomes necessary is in the adequate disposal of the glycerin by-product and the used wash-water. Current practice at the plant is to dump both glycerin and water outside, thereby requiring land for remediation. However, an expansion of biodiesel production could promote constructive use of the glycerin for, notably as an input to biogas production. Therefore, expanding the small-scale system may have positive impacts for land requirements, as long as sufficient used cooking oil is available.

The quality of the final energy product, the biodiesel, is difficult to assess fully. The biodiesel is used for transportation purposes, and in this respect, represents a full replacement of diesel. It is possible to run diesel engines using the waste cooking oil itself, thereby not requiring this upgrade in energy quality; however, this is rarely done due to operational reasons (gummed filters). For the present, the energy supply matches what Barbados desires, and, due to the simplicity of the operation, the input cooking oil could be processed in different ways to keep meeting what is defined on Barbados as high quality energy.

All things being equal, the biodiesel operation could not be scaled up and replace the current energy-producing infrastructure of Barbados. Small-scale biodiesel cannot power Barbados. While the specific EROI of the operation is not known, biodiesel in general does not have a high EROI (c.f. Sheehan and Camobreco 1998). To this end, the operation does not even attempt to supply its own energy needs, but rather relies on many external inputs (notably electricity and methanol). Furthermore, the ratio of labour to gross energy production seems high, given that the plant employed three full time workers to produce in the range of 300-600 gallons per week. This ratio would be much higher if one were to consider labour to net energy production. It is important to note, however, that the labour productivity of energy production is one area where energetics diverges from

other assessment frameworks, because others might justifiably argue that the high employment opportunities in the renewable energy sector represent a positive step towards sustainability (at least where unemployment or under-employment is a significant problem).

Whither small-scale biodiesel?

If small-scale biodiesel does not represent a potential replacement energy “heart” for Barbados, does it still have a role to play? Both the sustainability-resilience assessment and the brief energetics discussion suggest that the greatest potential for small-scale biodiesel lies in its ability to promote social learning. Biodiesel represents an promising transition fuel, in that it allows for gradual establishment of a new bio-based production infrastructure without radically altering the consumption infrastructure. Likewise, small-scale biodiesel may promote social transition. By facilitating endogenous energy production, linking a diversity of stakeholders, and promoting awareness and learning about critical issues, small-scale biodiesel production may serve as a key part of a social transformation upon which our energy transformation must be predicated. While this analysis supports the conclusion of Giampietro and Mayumi (2009) that bioenergy is unlikely to serve as a useful new energy “heart” for present society, the broader scope of considerations reveals that if properly undertaken, such small scale biodiesel operations could provide social learning benefits and a means of catalyzing a new approach to energy and society.

5. CONCLUSION

In principle, an assessment framework that incorporates sustainability purposes and appreciation of complex system realities is well suited to our times. The illustrative case here demonstrates that a comprehensive but minimally demanding sustainability-resilience-energetic based assessment of a modest existing undertaking can be feasible and illuminating. The assessment indicated that for the specific context at hand, the main benefit of biodiesel production is in promoting social learning and societal transformation, rather than offering any significant contributions to enhancing energy security and waste management, or replacing the energy ‘heart’ of Barbados. It also found that the most promising means of improving the operation lay in larger scale policy and programme initiatives rather than at the project level. Both results are insights unlikely to emerge from more narrowly scoped, conventional assessments focusing only on energetic, economic or biophysical concerns.

The approach described in this paper has some important limitations. Ideally, the kind of sustainability-resilience-energetic assessment explored here would be applied iteratively throughout the selection, planning, implementation and closure/renewal of undertakings large and small, rather than merely during implementation. In this case, it would have been better if an initial sustainability-resilience assessment had been performed at the beginning of the project, and reviewed several times throughout the life of the project. Furthermore, there is a need to incorporate the insights from energetics into sustainability-resilience assessments, rather than simply undertake a post-facto application of the kind described above. As previously noted, work is currently being undertaken in this regard. Finally, while the assessment involved key stakeholders in research process, broader consultation would have added to the legitimacy of the assessment and the plurality of perspectives.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Natural Sciences and Engineering Research Council of Canada, whose funding made this research possible.

REFERENCES

Barbados, G. (2004). *Solid Waste Management Program*. Retrieved February 11, 2009, from <http://www.solid.gov.bb/Programme/program04.asp>.

- BL&P. (2009). *How we make electricity*. Retrieved March 7, 2009, from <http://www.blpc.com.bb/aboutus/makeelectricity.cfm>.
- Buchholz, T., E. Rametsteiner, et al. (2009). *Multi Criteria Analysis for bioenergy systems assessments*. *Energy Policy* **37**(2): 484-495.
- EIA. (2009, December 17, 2008). *Barbados Energy Profile*. Retrieved February 11, 2009, from http://tonto.eia.doe.gov/country/country_energy_data.cfm?fips=BB.
- Funtowicz, S. O. and J. R. Ravetz (1993). "Science for the post-normal age." *Futures* **25**(7): 739-755.
- Gaudreau, K. and R. B. Gibson (2010). "Illustrating integrated sustainability and resilience based assessments: a small-scale biodiesel project in Barbados." *Impact Assessment and Project Appraisal* **28**(3).
- Giampietro, M. (2004). *Multi-scale integrated analysis of agroecosystems*. Boca Raton, CRC press.
- Giampietro, M. and K. Mayumi (2000). "Multiple-Scale Integrated Assessment of Societal Metabolism: Introducing the Approach." *Population & Environment* **22**(2): 109-153.
- Giampietro, M. and K. Mayumi (2009). *The biofuel delusion : the fallacy of large-scale agro-biofuel production*. London ; Sterling, Va., London ; Sterling, Va. : Earthscan.
- Gibson, R. B. (2006). *Sustainability-based assessment criteria and associated frameworks for evaluations and decisions: theory, practice and implications for the Mackenzie Gas Project Review*, Joint Review Panel for the Mackenzie Gas Project: 67.
- Gibson, R. B., S. Hassan, et al. (2005). *Sustainability Assessment - Criteria and Processes*. London, UK, Earthscan.
- Gibson, R. B., M. Winfield, et al. (2008). *An Analysis of the Ontario Power Authority's Consideration of Environmental Sustainability in Electricity System Planning*. Waterloo, Ontario, Green Energy Coalition, Pembina Institute, Ontario Sustainable Energy Association: 200.
- Gomiero, T. and M. Giampietro (2001). "Multiple-Scale Integrated Analysis of Farming Systems: The Thuong Lo Commune (Vietnamese Uplands) Case Study." *Population & Environment* **22**(3): 315-352.
- Gunderson, L. H. and C. S. Holling, Eds. (2002). *Panarchy : understanding transformations in human and natural systems*. Washington, Washington : Island Press.
- Hagens, N. J. and K. Mulder (2008). "A Framework for Energy Alternatives: Net Energy, Liebig's Law and Multi-criteria Analysis". *Biofuels, Solar and Wind as Renewable Energy Systems*. D. Pimentel. Dordrecht, Springer Netherlands: 295-319.
- Kemp, W. (2006). *Biodiesel - Basics and Beyond*. Tamworth, Ontario, Aztext Press.
- Mongabay. (2007). *Deforestation Rates in Barbados*. Retrieved March 12, 2009, from <http://rainforests.mongabay.com/stats/Barbados.htm>.
- Odum, H. T. (1995). "Self-Organization and Maximum Empower". *Maximum Power: The Ideas and Applications of H.T. Odum*. C. S. Hall. Colorado, University of Colorado Press: 311-330.
- Odum, H. T. (1996). *Environmental Accounting: EMERGY and environmental decision making*. New York, John Wiley.
- Phalakornkule, C., A. Petiruksakul, et al. (2009). "Biodiesel production in a small community: Case study in Thailand." *Resources, Conservation and Recycling* **53**(3): 129-135.
- ResAlliance (2007). *Assessing and managing resilience in social-ecological systems: A practitioners' workbook* : Version 1.0, The Resilience Alliance.
- ResAlliance (2007). *Assessing resilience in social-ecological systems: A scientist's workbook*, The Resilience Alliance.
- Sealy, H. (2006). *The Barbados Perspective of a Hydrogen Economy*. Bridgetown, Barbados, Barbados National Commission on Sustainable Development.
- Sheehan, J. and V. Camobreco (1998). *An Overview of Biodiesel and Petroleum Diesel Life Cycles*. Golden, Colorado, National Renewable Energy Laboratory: 48.
- Walker, B., C. S. Holling, et al. (2004). "Resilience, Adaptability and Transformability in Social-ecological Systems." *Ecology and Society*. **9**: 5.
- Walker, B. and D. Salt (2006). *Resilience Thinking - Sustaining Ecosystems and People in a Changing World*. Washington, D.C., Island Press.
- Winfield, M., R. B. Gibson, et al. (2010). "Implications of sustainability assessment for electricity system design: The case of the Ontario Power Authority's integrated power system plan." *Energy Policy* **38**(8): 12.
- WRI. (2006). *Agriculture and Food: Country Profile - Barbados*. Retrieved March 12, 2009, from <http://earthtrends.wri.org/text/agriculture-food/country-profile-15.html>.

INTEGRATED FOOD, ENERGY AND ENVIRONMENTAL SERVICES PRODUCTION AS AN ALTERNATIVE FOR SMALL RURAL PROPERTIES IN BRAZIL

Feni Agostinho and Enrique Ortega*

Ecological Engineering Laboratory, Food Eng. School, State University of Campinas

ABSTRACT

Alternative energy sources from fossil fuel are being envisioned and it is increasing the interest for energy derived from vegetal biomass. Specifically in Brazil, sugarcane ethanol is being intensively produced on large-scale, raising great social and environmental concerns about its production. Ethanol production systems with better balance between economic, social and environmental aspects must be envisioned, in which a systemic view approach needs to be considered in their assessment taking into account other human needs than only energy fuel. In this sense, the Integrated Food, Energy and Environmental Services Production (IFEES) on small-scale suggests an alternative. The aim of this work is to assess, in a multicriteria way, the environmental performance of a common IFEES found in Brazil and compare its performance indices against large-scale ethanol production. For this, energy embodied analysis, energy accounting, material flow accounting and gas emission inventory are used as tools. Results show that IFEES has better overall environmental performance than large-scale, and that ethanol produced by IFEES has better environmental performance as well. At the same time, IFEES produce several other by-products than only ethanol (i.e. food, forestry products, compost and environmental services), but large-scale ethanol productivity is 25 times higher than IFEES.

Keywords: Brazil; Ecological Rucksack; Energy; Emergy; Ethanol; Gas Emission

1. INTRODUCTION

Petroleum, natural gas and coal are responsible for providing almost 87% of total primary energy consumed worldwide, reducing its natural reserves by levels that will probably become unavailable in the next decade; this phenomenon is called "peak-oil" (Campbell and Laherrère, 1998; <http://www.peakoil.net>). In 2005, the major economies of the world, including the G8 and 5 developing nations (Mexico, India, Brazil, China, and South Africa), along with the United Nations, the International Energy Agency, and the European Union launched the Global Bioenergy Partnership to discuss ways to promote the sustained use and production of biofuels around the globe, reflecting growing concerns for finding economically viable substitutes for petroleum.

According to International Energy Agency (2004), it is expected that biofuel used worldwide for transportation will increase from the current 1% to 7% in 2030, which represents an increase from 15.5 million to 147 million tons of oil equivalent. Considering that, currently Brazil is responsible for about 33% of ethanol produced worldwide, certainly it has an important role supplying this biofuel to society. Brazilian government intends to increase and expand large-scale ethanol production, mainly in Sao Paulo State due to excellent climate conditions and infra-structure already installed (Cerqueira Leite et al, 2009).

* Corresponding author; E-mail: feniagostinho@gmail.com; Telephone: +55 19 35214058

Large-scale biofuel production and its expansion are being criticized by some researchers (Santa Barbara, 2007; Giampietro and Mayumi, 2009). There are several scientific papers and reports published about Brazilian ethanol production and its environmental performance (Oliveira et al, 2005; Macedo et al, 2008; Smeets et al, 2008; Luo et al, 2009; Pereira and Ortega, 2010; among others), but all of them focused on only one or two aspects of environmental performance and generally they are related to energy performance and/or dioxide carbon emissions. Moreover, large-scale production is considered as a tendency and only differences in its technological aspects are being assessed, disregarding the option to produce ethanol in small-scale. Assessing ethanol production systems through a life cycle approach and using different methodologies is mandatory to reach indicators with high quality to be considered by stakeholders and decision makers, but this assessment must take into account different processes and scales to produce energy, food and environmental services, which are also essentials for humans.

The objective of this work is to assess, through a multicriteria approach, the environmental performance of an Integrated Food, Energy and Environmental Services (IFEES) production in Brazil. Four main methodologies are used: Embodied Energy Analysis, Emergy Accounting, Material Flow Accounting and Gas Emission Inventory. A large-scale ethanol production in Brazil is also evaluated by the same approach, making it possible to compare it with IFEES results.

2. MATERIAL AND METHODS

2.1. Integrated Food, Energy and Environmental Services (IFEES) production

Considering all potential social-environmental problems related to large-scale ethanol production in Brazil, it is mandatory to find production systems that minimize them and provide more than energy, but also food and environmental services. Despite of energy issue is a crucial point nowadays, humans also need food and environmental services to survive. Moreover, social issues related to quality and quantity of labor is as important. In this sense, the IFEES tries to combine all these issues in a small family-managed rural property (30ha). Basically, the IFEES tries to use local raw material and labor to supply regional market with a series of different products, including energy as solid and liquid fuel, food (grains, vegetables, fruits, coffee, meat and milk) and environmental services provided by areas with natural vegetation.

The importance of IFEES is associated with its complexity that, according to Ulgiati et al (2007), these systems adapt to environmental conditions by optimizing, and not necessarily maximizing, their efficiency, so that global maximum power output can be achieved and maintained. Societies deplete most of the known and accessible resources storage, making them increasingly scarce. Therefore, according to the Maximum Empower Principle², rapid resource consumption is no longer a winning strategy for survival and must be replaced by increased global efficiency, i.e. producing more with available resources. Increasing the complexity of the system as well as the use of co-products helps to achieve a better performance and an optimum use of available resources.

It is well known that different regions have different raw materials and energy available for production, different climate conditions, soil types and social-cultural behavior. Thus, each region can reach its own balance between nature and economic activities, i.e. its own carrying capacity. Considering that Sao Paulo State is the focus of this work, all IFEES visited during the field work were taking into account in establishing an appropriated IFEES

² #1 - Maximum Empower Principle: "In the competition among self-organizing process, network designs that maximize empower will prevail" (Odum, 1996, p.16); #2 - "In self-organization patterns, systems develop those parts, process, and relationships that maximize useful empower" (Ulgiati et al, 2007, p.1362). Empower definition is the "emergy flow per unit time" (Odum, 1996, p.13).

containing characteristics of small rural properties located in Sao Paulo State. Table 1 shows the two systems considered as a case study: small-scale (IFEES) and large-scale.

2.2. Sustainability multi-criteria multi-scale assessment (SUMMA)

SUMMA approach is discussed by Ulgiati et al (2006), in which the authors employed a selection of “upstream”³ and “downstream” methods, which offer complementary points of view on the complex issue of environmental impact assessment. Each individual assessment method is applied according to its own set of rules. The calculated impact indicators are then interpreted within a comparative framework, in which the results of each method are set up against each other and contribute to providing a comprehensive picture in which conclusions can be drawn.

Table 1. Main characteristics of IFEES and large-scale ethanol production considered in this work.

Characteristic	Unit	IFEES (small-scale) ¹	Large-scale ²
System location	-	Sao Paulo State	Sao Paulo State
Time period for raw data	-	2010	2005-2008
Raw data source (average values)	-	Field work (3 IFEES)	Dataset (41 plants)
System area ³	ha	35	38,750
Sugarcane area	ha	2	31,000
Ethanol production capacity	L/day	65	860,000
Sugarcane productivity	ton/ha	65	87
Sugarcane area	ha	2	31,000
Sugarcane burned before harvesting	%	0	69
Crushed sugarcane	ton/day	1	9,965
Ethanol productivity	L/ton	65	86.3
Vinasse production ⁴	L/L ethanol	14	10
Sugarcane bagasse ⁵	kg/ton sugarcane	350	270
Agricultural management	-	Agroecological	Conventional

¹ Raw data from this work. ² Raw data from Macedo et al (2008) and Pereira and Ortega (2010). ³ For large-scale, it was not possible to find information about natural vegetation areas. Brazilian Federal laws establish that 20% of total area must be preserved (it is called as Legal Reserve, LR), added to Protecting Permanent Areas (APP, i.e. buffer on rivers and water springs). Thus, in this work it was assumed that total area with preserved natural vegetation corresponds to 20% of total large-scale area. ⁴ Vinasse is an ethanol production residue. It is a liquid residue with high concentration of organic matter and nutrients that demands high levels of oxygen to be dissolved. Large-scale vinasse is spread in the sugarcane field, while in IFEES it is supplied directly for cattle. ⁵ Sugarcane bagasse is the biomass residue from crushed sugarcane. For large-scale, sugarcane bagasse contains almost 0% of moisture and it is totally burned to produce steam and electricity. In the IFEES, sugarcane bagasse contains almost 20% of its initial moisture and it is used as food for cattle and also to produce compost.

Different from Ulgiati et al (2006), in this present work four methods were chosen to be applied on IFEES (small-scale) and large-scale ethanol production: (i) Embodied Energy Analysis, (ii) Material Flow Accounting, (iii) Emergy Accounting and (iv) Gas Emission Inventory.

2.2.1. Embodied energy analysis

Energy Analysis is defined by International Federation of Institutes for Advanced Study (IFIAS) as the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service. According to Franzese et al (2009), energy analysis aims to quantify the availability and use of stocks of fossil fuels, sometimes also referred to as commercial energy, i.e. fossil and fossil-equivalent energy. It focuses on fuels

³ The “upstream” methods are concerned with the inputs, and account for the depletion of environmental resources, while the “downstream” methods are applied to the output, and look at the environmental consequences of the emissions (Ulgiati et al, 2006).

and electricity, fertilizers and other chemicals, machinery, and assets supplied to a process in terms of the oil equivalent energy required to produce them. Embodied energy analysis of a product or process is calculated by the sum of all raw quantity of each input multiplied by its respective energy intensity factor. The more important final indicators of this methodology are (i) the total amount of energy consumed by the system and (ii) its energy transformation efficiency reflected by EROI index (Energy Return on Investment). Deeper understanding of Embodied Energy Analysis can be found mainly at Herendeen (1998) among others.

2.2.2. Material Flow Accounting

The Material Flow Accounting method (Schmidt-Bleek, 1993) aims to evaluate the environmental disturbance associated with the withdrawal of raw material from their natural ecosystem. For this, appropriate material intensity factors (MIF in mass/unit) are multiplied by each system's input, accounting for the total amount of abiotic matter, water, air and biotic matter that is directly or indirectly required by system under analysis (Ulgiati et al, 2006). This methodology supplies important information related to load on environment caused generally far from system location, showing the amount of abiotic matter, biotic matter and water consumed to produce the materials and energy used up by system under analysis.

2.2.3. Emergy accounting

Energy can be defined as the amount of work that can be performed by a force, based on the physical principle that potential energy is necessary. In accordance to the second law of thermodynamics, each transformation process degrades the available potential energy, but the "quality" of the remaining energy is increased. Energy quality is a crucial point related to Emergy Methodology and it is intensely discussed in Odum (1996). Since real wealth can be measured by the work previously done to produce something, emergy is considered a scientific measure of real wealth in terms of the energy previously required to make something (Odum, 1996), being recognized as a donor side approach. The classical emergy definition "is the available energy of one kind previously used up directly and indirectly to make a service or product" (Odum, 1996, p.7). Deeper understanding about emergy methodology rules and meanings can be found mainly at Odum (1996) and Brown and Ulgiati (2004).

In this work three modified emergy indices were considered instead of traditional ones: renewability, environmental loading ratio and emergy sustainability index. The partial renewabilities of each input were considered for their calculation, as proposed by Ortega et al (2002) and used by Agostinho et al (2010). In accordance to these authors, the incorporation of partial renewability is particularly accepted when the system uses materials and labor from local or regional economy, which could be renewable or, at least, partially renewable. The partial renewability values considered in this work were 30% for seedlings and 60% for electricity for both systems (IFEES and large-scale). Different values were considered for family labor (60% for IFEES), external labor (60% for IFEES and 30% for large-scale) and water (100% for IFEES and 50% for large-scale). For all other items, partial renewability was not considered.

Family labor is another complex issue and not yet well defined in emergy evaluation. Several emergy evaluations of large-scale agriculture have only a single output and frequently it uses external labor. Differently, small agricultural family-managed systems in Brazil produce several outputs instead of only one and it uses family labor within the system boundaries. According to emergy algebra (Odum, 1996), only those flows that cross the system boundaries must be accounted for, resulting in an exclusion of energy from internal family labor. The point is that the system needs that energy source to produce, and if it is assumed that family labor has a huge partial renewability (for instance 60%), the system's emergy renewability index will show lower performance when family labor is not accounted

for. Nevertheless, the system's Emery Yield Ratio (EYR)⁴ and Emery Investment Ratio (EIR)⁵ will show better performance when family labor is not accounted for. Due to these reasons, in this work the emery indices are calculated in different ways, considering and not considering the internal energy flow from family labor.

2.2.4. Gas Emission Inventory

Gas emission inventory supplies important information about global and local emissions. Due to current concerns about global warming, it is considered essential in any environmental assessment. This work focus on two categories of emission (Table 2): (i) Indirect gas emissions and (ii) Direct gas emissions. Indirect gas emissions are those related to production of materials used up by system; those emissions generally are located far from system location, nevertheless they cause global environmental load. To estimate the indirect emissions, firstly all materials used up by system were converted into their oil equivalents and then they were multiplied by the emission factors provided by USEPA (2008). Direct gas emissions are those caused locally by material and fuel burning. To estimate the direct gas emissions, only the diesel burned in engines was accounted for. The emission factors for combustion in tractors (USEPA, 2008) were considered. Both, directly and indirectly gas emissions, supply information about total CO, NO_x, PM10, SO₂, CH₄, N₂O and CO₂ released into the atmosphere. Additionally, global warming potential and acidification potential were estimated using the Jensen et al (1997) approach. As shown in Table 2, important emission sources were not considered due to the lack of emission factors available; in this work an Excel® spreadsheet was used instead of Life Cycle Assessment software and/or other software that simulates ethanol industrial process.

Table 2. Emission sources considered in this work.

Emission source	IFEES	Large-scale
Indirect emissions (global environmental load)		
Materials ¹	Considered	Considered
Direct emissions (local environmental load)		
Direct diesel burned in engines	Considered	Considered
Sugarcane burned before harvesting	²	Not considered
Sugarcane bagasse burned to produce steam and electricity	³	Not considered
Sugar fermentation process	Not considered	Not considered
Emissions from soil due to fertilizer use	Not considered	Not considered
Fermentation of organic manure (compost)	Not considered	⁴
Land use change	Not considered	Not considered

¹ Emissions from material production. ² IFEES does not burn sugarcane before harvesting. Large-scale adopts this practice in 69% of all sugarcane areas. ³ Instead of burning sugarcane bagasse to produce steam, IFEES uses wood biomass. This wood biomass was not accounted for in this work. ⁴ Large-scale does not produce organic compost and all sugarcane bagasse is burned to produce steam and electricity.

3. RESULTS AND DISCUSSION

3.1. Characteristics of the IFEES and large-scale ethanol production

Figure 1 shows the systemic diagram of the IFEES considered in this work. First and foremost it must be observed the complexity of this system, in which there are different land

⁴ Emery yield ratio (EYR) is a measure of the system's ability to exploit and make natural resources available (Brown and Ulgiati, 2004) through external economic investment. Thus, EYR assesses the system's dependency on non-renewable resources from the economy, in which higher EYR values mean better performance.

⁵ Emery investment ratio (EIR) measures the intensity of invested emery (Brown and Ulgiati, 2004) from the external economy. It assesses the relationship between the nonrenewable resources from the economy and natural resources. Lower EIR values mean more efficiency in economic resource allocation.

uses (natural capital, tree plantation, sugarcane, pasture, horticulture, annual culture, orchard and coffee) and several internal feed-back of material and energy flows. Moreover, several outputs are produced instead of only one (wood as solid fuel, wood for construction, trees for landscaping, ethanol, organic manure, meat, milk, grains, fruits and vegetables), and the system uses local labor to manage its activities. In small-scale, family labor and also external (but local) labor are generally synonymous with good quality labor and do not have all the social problems related to large-scale ethanol production. Small-scale agricultural production generally has large areas with preserved natural vegetation that are responsible for production of several environmental services used up internally to the system boundaries and also exported to the surrounding region. At the same time, it is recognized that all human-dominated systems of any scale produce negative externalities, but due to ecological agricultural management, small-scale systems produce less negative externalities than large-scale ones.

Table 3 shows all input and output used by IFEEES and large-scale ethanol production systems. Considering the inputs, the main differences are related to: high use of water, seedlings, agrochemicals and diesel by large-scale; IFEEES uses electricity produced outside of its system boundaries, large amounts of wood and concrete; considered as an important social indicator, the number of labor hours for IFEEES is much bigger than large-scale (302 h/ha/yr for IFEEES and 86 h/ha/yr for large-scale). Concerning the output, large-scale produces 6,000 L/ha/yr of ethanol and 25GWh/yr of electricity, while IFEEES produces only 241 L/ha/yr of ethanol. On the other hand, IFEEES produces annually 4.8 tons of food per ha, 0.6 tons wood per ha and 4.8 tons of organic manure per ha, while large-scale does not produce these items. Moreover, IFEEES produces 1,440 m³/ha/yr of water and can convert annually 11.6 tons of CO₂ per ha in vegetal biomass through its preserved natural vegetation areas; large-scale produces 840 m³/ha/yr of water and converts annually 6.7 tons of CO₂ per ha. Diversity in production and its quantity in mass units are good indicators, but alone they are not enough to make a decision about what production system should be adopted. Due to that, in the next topics, the environmental systems performance is discussed through SUMMA approach, supplying essential indicators that should be taken into account simultaneously with the production output indicators.

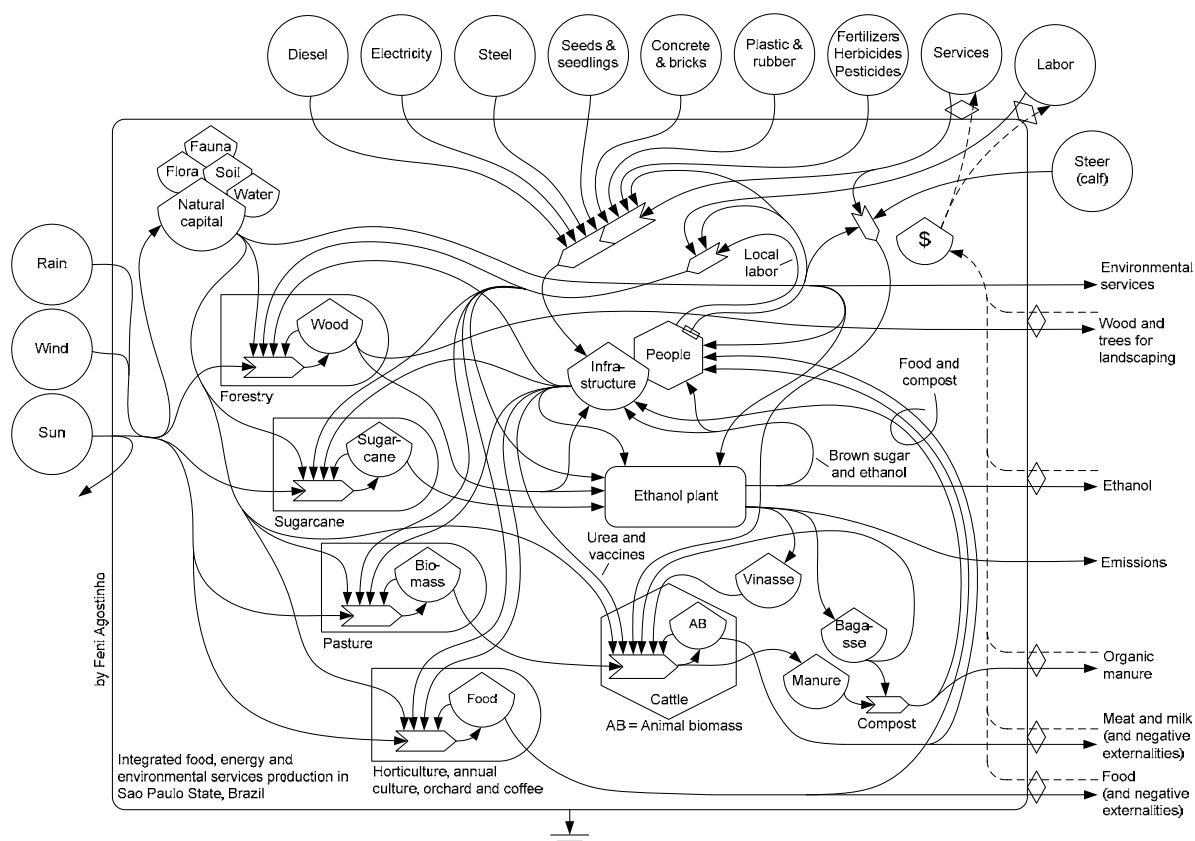


Figure 1. Systemic diagram of Integrated Food, Energy and Environmental Services (IFEES) production.

3.2. SUMMA's results

3.2.1. Energetic-environmental impact by overall systems

Embodied energy index

Energy efficiency can usually be defined as a ratio between the energy produced by a system and the energy used to produce that quantity of energy, i.e. a kind of output/input relationship. Thus, energy efficiency measures the system capacity to transform one kind of energy in another one, in which high values means high efficiency. Energy efficiency is represented by Energy Return on Investment (EROI) index in embodied energy analysis. Table 4 shows that the overall energy efficiency (EROI) for IFEES is 18 while for large-scale is 11, indicating better efficiency for IFEES; it means that 18 units of energy are produced for each unit used up by IFEES system. It sounds odd a system create energy because it goes against the thermodynamic laws (1st law: energy cannot be created), but embodied energy analysis allows this kind of results because its algebra does not include the energy provided by nature. IFEES is about 1.6 times more efficient than large-scale, but it must be highlighted that this efficiency reflects all energy produced, including ethanol, food, forestry products and compost.

Table 3. Raw data for IFEES and large-scale ethanol production.

Input Item	Unit	IFEES	Large-scale
Sun	kWh/m ² /day	5.00	5.00
Rain	m ³ /m ² /yr	1.40	1.40
Wind	m/s	4.70	4.70
Water ¹	kg/ha/yr	687.14	110,519.23
Soil loss	kg soil/ha/yr	5,000.00	11,900.00
Concrete	kg/ha/yr	53.34	1.15
Steel	kg/ha/yr	7.37	9.62

Copper (heat transfer) ²	kg/ha/yr	0.05	0.05
Wood lumber	kg/ha/yr	36.20	-
Rubber (tractor tire)	kg/ha/yr	0.48	2.51
Plastic (PVC pipeline)	kg/ha/yr	0.16	-
Clay brick and tile	kg/ha/yr	9.52	-
Electricity	kWh/yr	8,000.00	-
Calcareous dolomite ³	kg/ha/yr	62.40	760.00
Nitrogen	kg/ha/yr	3.20	76.00
Phosphorus	kg/ha/yr	7.46	42.00
Potassium	kg/ha/yr	5.60	115.00
Urea	kg/ha/yr	4.80	-
Diesel	L/ha/yr	40.82	230.00
Seeds	kg/ha/yr	1.63	-
Seedlings	kg/ha/yr	139.00	2,800.00
Steer (calf; meat)	kg/ha/yr	13.71	-
Package (polyethylene)	kg/ha/yr	5.71	-
Herbicide	kg/ha/yr	-	0.16
Insecticide	kg/ha/yr	-	2.20
External labor: Permanent and Provisory ⁴	h/ha/yr	60.34 and zero	25.46 and 61.29
Family labor	h/ha/yr	241.37	-
Services ⁵	USD/ha/yr	66.30	482.00
Output Item	Unit	IFEES	Large-scale
Ethanol	L/ha/yr	241	6,006
Electricity ⁶	kWh/yr	-	24,812,400
Food ⁷	kg/ha/yr	4,779	-
Forestry (construction and landscaping)	kg/ha/yr	640	-
Compost (organic manure)	kg/ha/yr	4867	-
Envir. Services: Water infiltration ⁸	L _{water} /ha/yr	1,440,000	840,000
Carbon dioxide absorbed ⁹	kgCO ₂ /ha/yr	11,615	6,776

Large-scale data from Macedo et al (2008) and Pereira and Ortega (2010); material consumption was divided by 30 years-lifetime; ethanol density of 0.8 kg/L. ¹ Water consumption for large-scale is 18.4 L water/L ethanol or 1.6 m³ water/ton crushed sugarcane (Pereira and Ortega, 2010). It includes only industrial phase, because sugarcane irrigation in Sao Paulo State is used only in special cases due to excellent climate conditions. ² For large-scale it was estimated as 0.5% of its total steel used. ³ Macedo et al (2008) used a value of 1900 kg/ha, but it is not clear if this value is annual or for five years period of sugarcane. Due to that, other references were used and the following value was adopted: 1900 kg/ha at the first year cut and 1900 kg/ha at the third year cut. Thus, the annual value obtained is 760 kg/ha/yr. ⁴ Provisory workers for sugarcane harvest season (270 workdays/year). These workers are generally related to several social problems that were not discussed in this present work. ⁵ Services include taxes, market price of all economic inputs, labor and also negative externalities of 230 USD/ha/yr for large-scale and 60 USD/ha/yr for small-scale (Pretty et al, 2005). ⁶ Electricity produced and exported of 9.2 kWh/ton sugarcane (Macedo et al, 2008). ⁷ Food includes Vegetables (7.9%), Grains (21.4%), Fruits (64.7%), Coffee (3.2%), Meat (1.1%) and Milk (1.7%). ⁸ Rainfall of 1.4 m³/m²/yr; IFEES has 7ha of Legal Reserve (LR) and 5ha of Permanent Protection Areas (PPA), both occupied with natural vegetation; assuming a hydric balance in which 30% of rainfall in natural vegetation is percolated into the soil. For large-scale it was assumed that 20% of its total area is taken by natural vegetation, which correspond to 7,750ha. ⁹ Net Primary Productivity for a tropical forest of 925 gC/m²/yr (Amthor, 1998).

Table 4. Embodied energy, emergy accounting and gas emission indices¹.

Methodology	Unit	IFEES	Large-scale	Large-scale ²
Embodied Energy				
EROI - Energy Return on Investment	-	18.12	11.41	8.20
Emergy Accounting				
Tr - Transformity	seJ/J	61,100	42,600	48,804
%R - Renewability ³	%	54	28	31
EYR - Emergy Yield Ratio	-	1.70	1.66	1.57
EYR - Emergy Yield Ratio ⁴	-	2.27	1.66	-
EIR - Emergy Investment Ratio	-	1.42	1.53	1.74
EIR - Emergy Investment Ratio ⁴	-	0.79	1.53	-
ELR - Environmental Loading Ratio ³	-	0.84	2.56	2.23
ESI - Emergy Sustainability Index ³	-	2.04	0.65	0.71
ESI - Emergy Sustainability Index ^{3,4}	-	2.71	0.65	-
Gas Emission				

Global warming potential	kg CO ₂ -eq./ha/yr	458.62	1,411.23	-
Acidification potential	g SO ₂ -eq./ha/yr	212.80	446.01	-

¹ Observation: These indices correspond to the systems as a whole, not for one output alone. ² Reference data from Pereira and Ortega, 2010. ³ Considering partial renewability of each system's input. ⁴ Not considering family labor located internally to system boundaries.

Emergy indices

All emergy indices calculated for large-scale in this work are close to the values found by Pereira and Ortega (2010) and also observed in Table 4. Transformity is the solar emergy required to make one Joule of a service or a product, expressing system efficiency and its output quality, i.e. bigger transformities represent low system efficiency but high quality of output systems (and vice-versa). Table 4 shows that the overall emergy efficiency is better for large-scale (43,000 seJ/J) than IFEES (61,000 seJ/J).

Renewability index shows high renewability for IFEES (54%) compared to large-scale (28%), indicating strong sustainability for IFEES and an unsustainable scenario for large-scale. Since non-renewable resources (basically derived from petroleum and mineral ores) are the driving forces of current large-scale ethanol production, their depletion over the next decades will be a great challenge for large-scale production.

EYR shows a similar dependency on economic resources for both systems of about 60% (EYR of 1.70 for IFEES and 1.66 for large-scale). This reflects that whether the system scale is small or large, the dependency on economic resources is high and it should be drastically reduced. An increase of renewable inputs is extremely important because high use of renewable resources will be advantageous in a future scenario of lesser oil availability. Production systems based on non-renewable resources will not be able to compete with others characterized by low oil dependency and greater contribution of renewable resources. When internal labor (family labor) is not accounted for, IFEES shows an EYR of 2.27 representing reduction of the dependency on economic resources from 60% to 44%.

As well as EYR, the EIR index shows similar performances for both systems, reaching 1.42 for IFEES and 1.53 for large-scale. This indicates that, for each unit of energy from nature, from 1.42 to 1.53 units of energy from economy are necessary, indicating high dependence on economic resources. The use of ecological management is urgent to increase the system's ability to use local renewable resources with low external investment. When internal labor (family labor) is not accounted for, EIR shows a value of 0.79 for IFEES, indicating a significant improvement in system performance.

ELR shows a low load on environment caused by small-scale (0.84), while large-scale causes moderate load (2.56). This load is a reflection of the systems dependency on non-renewable resources.

ESI shows better cost/benefit (benefit provided to society through a load on environment) relationship for IFEES than large-scale (2.04 and 0.65 respectively). The differences are increased when internal labor (family labor) is not accounted for, resulting in a value of 2.71.

Gas emission indices

Global warming (or greenhouse effect) is the effect of increasing temperature in the lower atmosphere. The lower atmosphere is normally heated by incoming radiation from the outer atmosphere. A part of the radiation is normally reflected by the soil surface but the carbon dioxide and other "greenhouse" gasses in the atmosphere reflect the radiation back to Earth resulting in the greenhouse effect, i.e. an increase of temperature in the lower atmosphere to a level above normal. There is no way to say what quantity of greenhouses gases released will increase the Earth's temperature to a determined degree, but Global Warming Potential is important to show the quantity of greenhouses gases released by production systems; this index is considered as an environmental parameter by decision makers. Table 4 shows that IFEES system releases 460 kgCO₂-eq./ha/yr while large-scale

releases 1,400 kgCO_{2-eq}/ha/yr, i.e. large-scale has a global warming potential about 3 times bigger than IFEES.

Acidification is caused by releases of protons in the terrestrial or aquatic ecosystems. In the terrestrial ecosystem the effects are seen as inefficient growth and, as a final consequence, dieback in softwood forests (e.g. spruce). Just as in global warming potential, it is not possible to establish a relation between the quantity of released gases and its acidification impact, nevertheless, acidification potential is another important index for environmental assessments. Table 4 shows an acidification potential of IFEES of 213 gSO_{2-eq}/ha/yr while large-scale has a value of 446 kgSO_{2-eq}/ha/yr, i.e. large-scale has an acidification potential about 2 times bigger than IFEES.

3.2.2. Energetic-environmental impact of sugarcane ethanol production

Table 5 shows that the energy required to produce one kilogram of ethanol by large-scale (2.60 MJ) is about 1.6 times bigger than IFEES (1.64 MJ), showing better energy efficiency for IFEES. This is reflected by EROI index, in which, for each Joule consumed by IFEES, 18J of ethanol are produced; for large-scale this relationship is 1J for 11J of ethanol.

Specific emergy index shows that large-scale is 27 times more efficient than IFEES if only ethanol is taken into account, because to produce 1g of ethanol are necessary 1.28E+9 seJ in large-scale, while in IFEES are necessary 3.45E+10 seJ. But these numbers are misleading. The point is that IFEES produces several output in addition to ethanol, and considering that emergy evaluation does not allow an allocation procedure, the energy content in ethanol produced was divided by total emergy used by IFEES, resulting in low efficiency. On the other hand, large-scale produces basically ethanol, and thus it makes sense that all inputs are used up to produce only ethanol. A fair comparison should be made comparing small-scale system producing only ethanol to large-scale ethanol production.

Material flow accounting shows a huge advantage for ethanol produced by IFEES compared to large-scale. For 1kg of ethanol produced by IFEES, 1.49kg of abiotic material (non-organic material), 0.11kg of biotic material (organic material) and 29.72kg of water are necessary, while for large-scale system are necessary 4.85kg of abiotic material (non-organic material), 0.24kg of biotic material (organic material) and 350kg of water. The biggest difference is related to water consumption, in which large-scale uses about 12 times more water to produce 1kg of ethanol than IFEES.

In reference to gas emissions, ethanol produced by IFEES has better performance when compared to large-scale (Table 5). Except for hydrocarbons, large-scale releases large amounts of gases to produce one ton of ethanol. The main differences are in CO₂, PM10 and N₂O emissions, in which large-scale release respectively 2.31, 2.01 and 2.19 times more than IFEES. Another important point is that about 10,000 times more mass of CO₂ per mass of ethanol is released by both systems when compared to the gases released.

Table 5. Environmental impact indicators per unit of ethanol¹.

Methodology	Unit	IFEES	Large-scale	Large/IFEES ratio
Embodied energy				
Energy intensity	MJ/kg	1.64	2.60	1.58
Energy return on investment (EROI)	-	18.12	11.41	0.63
Emergy accounting				
Specific emergy (with L&S) ²	seJ/g	3.45E+10	1.28E+09	0.037
Specific emergy (without L&S)	seJ/g	2.21E+10	9.66E+08	0.044
Transformity (with L&S)	seJ/J	1.16E+06	4.32E+04	0.038
Transformity (without L&S)	seJ/J	7.45E+05	3.26E+04	0.044
Material flow accounting				
Abiotic material consumption	kg _{abiotic} /kg	1.49	4.85	3.25
Biotic material consumption	kg _{biotic} /kg	0.11	0.24	2.18
Water consumption	kg _{water} /kg	29.72	350.03	11.78
Gas emission				
Hydrocarbons ³ released	g hydr./ton	2.88	2.55	0.88

Carbon monoxide released	g CO/ton	34.24	64.39	1.88
Nitrogen oxide released	g NOx/ton	51.13	75.82	1.48
Particulate matter released	g PM10/ton	6.20	12.50	2.01
Sulfur dioxide released	g SO ₂ /ton	13.04	24.62	1.88
Methane released	g CH ₄ /ton	0.22	0.31	1.41
Nitrous oxide released	g N ₂ O/ton	0.64	1.40	2.19
Carbon dioxide released	g CO ₂ /ton	124,813.00	288,481.18	2.31
Global warming potential	kg CO ₂ -eq./ton	125.08	289.02	2.31
Acidification potential	g SO ₂ -eq./ton	58.03	91.34	1.57

¹ Allocation in energy units. ² L&S means Labor and Services. ³ Assuming CH₂ as a basic hydrocarbon

3.2.3. General discussion

Considering all environmental impact indicators shown in Tables 4 and 5 and the above discussion, the advantage of ethanol produced by IFEES is evident, because it causes a lesser load on the environment for each unit of ethanol produced and also its overall system performance is better than large-scale. Nevertheless, Table 3 shows that the amount of ethanol produced by IFEES is 25 times lesser than large-scale. This indicates that if large-scale ethanol production were substituted by IFEES, it should be necessary 25 times more land than the current 5.5 millions of hectares taken by sugarcane in Sao Paulo State to supply the current demand for ethanol. Is there available land for this? Or should society reduce its energy dependence in order to live within the limits of the available land to produce ethanol in small scale? Will the sugarcane expansion result in food versus energy competition? How will poor and indigenous people be affected by that expansion? These and other important issues are not discussed in this work. The aim is to show the environmental performance of small-scale and large-scale ethanol production, in which a new production model (IFEES) is proposed to produce more than only energy. Those issues are discussed by Giampietro and Mayumi (2009), Santa Barbara (2007), Odum and Odum (2001), among others.

It is well-know that any man-made process causes some load on environment. The point is that nowadays the Earth's carrying capacity is much lesser than one hundred years ago; thus, today's environmental load must be carefully controlled and reduced. Society needs mainly food, environmental services and energy to survive, and the processes chosen to produce them must be those more sustainable, assessed through a multicriteria approach in which economic, social and environmental issues are taken into account.

4. CONCLUSION

(a) Integrated Food, Energy and Environmental Services (IFEES) production has better overall environmental performance than large-scale ethanol production, because it has higher renewability (54% versus 28%), lower environmental load (0.84 versus 2.56), higher sustainability index (2.04 versus 0.65), higher energy return on investment (18 versus 11), lower global warming potential (460 versus 1,400 kgCO₂-eq./ha/yr) and lower acidification potential (213 versus 446 gSO₂-eq./ha/yr). Both systems have approximately the same performance for transformity (61,000 seJ/J and 43,000 seJ/J), emergy yield ratio (1.70 and 1.66) and emergy investment ratio (1.42 and 1.53).

(b) Sugarcane ethanol produced by IFEES causes less environmental impact than large-scale, because it demands less invested energy (1.64 versus 2.60 MJ/kg_{EIOH}), consumes less abiotic matter (1.49 versus 4.85 kg/kg_{EIOH}), less biotic matter (0.11 and 0.24 kg/kg_{EIOH}) and less water (30 versus 350 kg/kg_{EIOH}). Moreover, ethanol from IFEES releases less CO, NO_x, PM10, SO₂, CH₄, N₂O and CO₂ than large-scale, resulting in a smaller global warming potential (125 versus 289 kgCO₂-eq./ton_{EIOH}) and smaller acidification potential (58 versus 91 gSO₂-eq./ton_{EIOH}). Both systems release almost the same amount hydrocarbons (2.88 and 2.55 ghydr./ton_{EIOH}).

The environmental advantage of IFEEES is evident when compared to large-scale ethanol production. IFEEES produces more than just ethanol, it also produce food, forestry products, compost and environmental services. On the other hand, large-scale produces high amounts of ethanol and electricity. If the current large-scale ethanol production were to be replaced by IFEEES, 25 times the current area occupied by sugarcane in Sao Paulo State would be necessary; but if large-scale ethanol production remains, all food, forestry products and part of environmental services produced by IFEEES will be not available and could result in social and environmental concerns. At this point, all pros and cons must be considered by decision makers, but always taking into account the benefits for all of society.

ACKNOWLEDGEMENTS

Feni Agostinho is grateful to Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP, process number 2009/51705-9) for Post-Doctor scholarship.

REFERENCES

- Agostinho, F., Ambrosio, L.A., Ortega, E., 2010. "Assessment of a large watershed in Brazil using emergy evaluation and geographical information system". *Ecological Modelling*, 221: 1209-1220.
- Amthor, J.S., 1998. "Terrestrial ecosystem responses to global change: a research strategy". In: *Distributed Active Archive Center for Biogeochemical Dynamics*, Oak Ridge National Laboratory. Available at http://daac.ornl.gov/NPP/other_files/worldnpp1.txt. Accessed on August 10th, 2010.
- Bastianoni, S., Campbell, D., Susani, L., Tiezzi, E., 2005. "The solar transformity of oil and petroleum natural gas". *Ecological Modelling* 186, 212–220.
- Boustead, I., Hancock, G.F., 1979. *Handbook of industrial energy analysis*. Ellis Horwood Publishers, England, 422p.
- Brandt-Williams, S.L., 2002. *Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios*. Folio no. 4 (accessed on March 22nd, 2006). Available at: <http://www.emergysystems.org/folios.php>.
- Brown, M.T., Ulgiati, S., 2004. "Emergy analysis and environmental accounting". *Encyclopedia of Energy* 2, 329–354.
- Buranakarn, V. 1998. *Evaluation of recycling and reuse of building materials using the emergy analysis method*. Ph.D. thesis.
- Campbell C., Laherrère J., 1998. The End of Cheap Oil. *Scientific American*, March 1998: 60-65.
- Cavalett, O., Ortega, E., 2010. "Integrated environmental assessment of biodiesel production from soybean in Brazil". *Journal of Cleaner Production*, 18: 55-70.
- Cerqueira Leite, R.C., Leal, M.R.L.V., Cortez, L.A.B., Griffin, W.M., Scandiffio, M.I.G., 2009. "Can Brazil replace 5% of the 2025 gasoline world demand with ethanol?" *Energy*, 34: 655-661.
- Coelho, O., Ortega, E., Comar, V., 2003. "Emergy assessment of Brazil using statistics of 1996, 1989 and 1981". In: *Ecological Engineering and Sustainable Agriculture* (accessed on January 17th, 2006) (in Portuguese). Available at: <http://www.fea.unicamp.br/docentes/ortega/livro/C05-Brasil-COC.pdf>.
- Cuadra, M., Rydberg, T., 2006. "Emergy evaluation on the production, processing and export of coffee in Nicaragua". *Ecological Modelling* 196, 421–433.
- USEPA, 2008. U.S. *Environmental Protection Agency, Technology Transfer Network Clearinghouse for Inventories & Emissions Factors*. Available at <http://www.epa.gov/ttn/chief/ap42/index.html>. Accessed on December 19th, 2008.
- Franzese, P.P., Rydberg, T., Russo, G.F., Ulgiati, S., 2009. "Sustainable biomass production: a comparison between gross energy requirement and emergy synthesis methods". *Ecological Indicators*, 9: 959-970.
- Giampietro, M., Mayumi, K., 2009. *The biofuel delusion: the fallacy of large-scale agro-biofuel production*. Earthscan, London, Sterling, VA, 320pp.

- Herendeen, R., 1998. "Embodied energy, embodied everything . . . now what?" In: *Proceedings of the 1st International Workshop Advances in Energy Studies. Energy Flows in Ecology and Economy*, 13-48/642, MUSIS, Roma, Italy.
- International Energy Agency (IEA), 2004. *Biofuels for transport - an international perspective*. Available at <http://www.iea.org>. Accessed on April 4th, 2009.
- Jarach, M., 1985. "Sui valori di equivalenza per l'analisi e il bilancio energetici in agricoltura". *Riv. di Ing. Agr.* 2, 102-114.
- Jensen, A.A., Hoffman, L., Moller, B.T., Schmidt, A., Christiansen, K., Elkington, J., van Dijk, F., 1997. "Life cycle assessment: a guide to approaches, experiences and information sources". *Environmental Issues Series*, n°6. European Environment Agency. Available at <http://www.eea.europa.eu/publications/GH-07-97-595-EN-C>. Accessed on July 28th, 2010.
- Luchi, F., Ulgiati, S. 2000. "Energy and emergy assessment of municipal waste collection. A case study". In: *Proceedings of the First Biennial emergy analysis research conference*. Brown (Ed.). USA. Center for Environmental Policy. University of Florida. Gainesville. FL.
- Luo, L., van der Voet, E., Huppes, G., 2009. "Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil". *Renewable and Sustainable Energy Reviews*, 13: 1613-1619.
- Macedo, I.C., Seabra, J.E.A., Silva, J.E.A.R., 2008. "Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020". *Biomass & Bioenergy*, 32: 582-595.
- Odum, H.T., 1996. *Environmental Accounting, Emergy and Decision Making*.
- Odum, H.T., E.C. Odum, R. King & R. Richardson. 1987. *Ecology and economy: emergy analysis and public policy in Texas. Energy systems in Texas and the United States*. University of Texas. Policy research project report number, 78. The Board of Regents.
- Odum, H.T., Brown, M.T., Brandt-Williams, S.L., 2000. *Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios*. Folio no. 1 (accessed on March 22nd, 2006). Available at: <http://www.emergysystems.org/folios.php>.
- Odum, H.T., Odum, E.C., 2001. *A Prosperous Way Down: Principles and Policies*. University Press of Colorado, Boulder, 326 pp.
- Oliveira, M.E.D., Vaughan, B.E., Rykiel Jr., E.J., 2005. "Ethanol as fuel: energy, carbon dioxide balances and ecological footprint". *Bioscience*, 55: 593-602.
- Ortega, E., Anami, M., Diniz, G., 2002. "Certification of food products using emergy analysis". In: *Proceedings of 3rd International Workshop Advances in Energy Studies, Porto Venere, Italy*, pp. 227–237 (accessed on July 7th, 2008). Available at: <http://www.chim.unisi.it/portovenere>.
- Ozkan, B., Akcaoz, H., Karadeniz, 2004. "Energy requirement and economic analysis of citrus production in Turkey". *Energy Conversion and Management* 45, 1821-1830.
- Pretty, J.N., Ball, A.S., Lang, T., Morison, J.I.L., 2005. "Farm costs and food miles: an assessment of the full cost of the UK weekly food basket". *Food Policy* 30, 1–19.
- Pereira, C.L.F., Ortega, E., 2010. "Sustainability assessment of large-scale ethanol production from sugarcane". *Journal of Cleaner Production*, 18: 77-82.
- Santa Barbara, J., 2007. *The false promise of biofuels. A special report from The International Forum On Globalization And The Institute For Policy Studies*. Available at <http://www.ifg.org/pdf/biofuels.pdf>. Accessed on August 4th, 2010.
- Schmidt-Bleek, F., 1993. "MIPS re-visited". *Fresenius Environ. Bull.* 2, 407–412.
- Smeets, E., Junginger, M., Faaij, A., Walter, A., Dolzan, P., Turkenburg, W., 2008. "The sustainability of Brazilian ethanol – an assessment of the possibilities of certified production". *Biomass & Bioenergy*, 32: 781-813.
- Ulgiati, S., Raugei, M., Bargigli, S., 2006. "Overcoming the inadequacy of single criterion approaches to Life Cycle Assessment". *Ecological Modelling* 190, 432–442.
- Ulgiati, S., Bargigli, S., Raugei, M., 2007. "An emergy evaluation of complexity, information and technology towards maximum power and zero emissions". *Journal of Cleaner Production*, 15: 1359-1372.
- WICEE, 2003. *Material intensity of material, fuel, transport services*. Version 2; 28.10.2003. Wuppertal Institute for Climate, Environment and Energy Available at http://www.wupperinst.org/de/projekte/themen_online/mips/. Accessed on June 24th, 2010.

Appendix A. Intensity factors used in this work.

Item	Emergy ¹	Unit	Ref.	Energy ²	Unit	Ref.	Material flow		Unit	Ref.
							Abiotic	Biotic		
1. Sun	1.00E00	seJ/J	[a]	-	-	-	-	-	-	-
2. Rain	3.10E04	seJ/J	[b]	-	-	-	-	-	-	-
3. Wind	2.45E03	seJ/J	[b]	-	-	-	-	-	-	-
4. Water	6.89E04	seJ/J	[c]	-	-	-	-	-	-	-
5. Soil loss	1.24E05	seJ/J	[d]	-	-	-	-	-	-	-
6. Concrete	2.42E12	seJ/kg	[e]	160	kgeq/ton	[l]	0.66	0.04	kg/kg	[o]
7. Steel	1.13E13	seJ/kg	[c]	1000	kgeq/ton	[l]	1.33	0.00	kg/kg	[p]
8. Cooper	3.36E12	seJ/kg	[c]	1500	kgeq/ton	[l]	9.32	0.00	kg/kg	[p]
9. Wood lumber	1.40E12	seJ/kg	[e]	390	kgeq/ton	[l]	170.07	0.00	kg/kg	[p]
10. Rubber	7.22E12	seJ/kg	[f]	2040	kgeq/ton	[m]	0.68	4.72	kg/kg	[p]
11. Plastic (PVC)	9.86E12	seJ/kg	[e]	3000	kgeq/ton	[l]	5.70	0.00	kg/kg	[q]
12. Clay brick and tile	3.75E12	seJ/kg	[e]	100	kgeq/ton	[l]	3.33	0.00	kg/kg	[p]
13. Electricity	2.52E05	seJ/J	[c]	250	kgeq/MWh	[l]	2.11	0.00	kg/kg	[p]
14. Lime	1.00E12	seJ/kg	[d]	220	kgeq/ton	[m]	4.70	0.00	kg/kWh	[p]
15. Nitrogen	6.38E12	seJ/kg	[c]	1440	kgeq/ton	[n]	1.44	0.00	kg/kg	[p]
16. Phosphorus	6.55E12	seJ/kg	[c]	260	kgeq/ton	[n]	1.10	0.00	kg/kg	[r]
17. Potassium	2.92E12	seJ/kg	[a]	160	kgeq/ton	[n]	7.36	0.00	kg/kg	[p]
18. Urea	6.38E12	seJ/kg	[g]	860	kgeq/ton	[l]	11.32	0.00	kg/kg	[p]
19. Diesel	9.21E04	seJ/J	[h]	1580	kgeq/ton	[n]	3.45	0.00	kg/kg	[p]
20. Seeds	5.88E07	seJ/kg	[c]	340	kgeq/ton	[l]	1.36	0.00	kg/kg	[p]
21. Seedlings	1.41E11	seJ/kg	[l]	38	kgeq/ton	[l]	4.62	0.24	kg/kg	[r]
22. Steer (calf; meat)	4.85E13	seJ/kg	[d]	240	kgeq/ton	[l]	4.62	0.24	kg/kg	[s]
23. Package (polyethylene)	1.50E12	seJ/kg	[l]	3000	kgeq/ton	[l]	-	-	-	[t]
24. Herbicide	2.49E13	seJ/kg	[c]	5670	kgeq/ton	[n]	2.12	0.00	kg/kg	[p]
25. Insecticide	2.49E13	seJ/kg	[c]	4740	kgeq/ton	[n]	1.10	0.00	kg/kg	[r]
26. Labor	7.21E12	seJ/h	[c]	-	-	-	1.10	0.00	kg/kg	[u]
Brazilian's emdolar	3.30E12	seJ/USD	[k]	-	-	-	-	-	-	-

¹ Emergy intensity values without accounting for labor and services and considering an emergy baseline of 15.83E+24 seJ/yr from Brown and Ulgiati (2004).

² eq. = equivalent oil; 1 toneq. = 42 GJ (Jarach, 1985).

[a] Odum, 1996; [b] Odum et al, 2000; [c] Brown and Ulgiati, 2004; [d] Brandt-Williams, 2002; [e] Buranakarn, 1998; [f] Odum et al, 1987; [g] Cuadra and Rydberg, 2006; [h] Bastianoni et al, 2005; [i] Estimated in this work; [j] Luchi and Ulgiati, 2000; [k] Coelho et al., 2003; [l] Jarach, 1985; [m] Boustead and Hancock, 1979; [n] Ozkan et al, 2004; [o] Assuming a soil with 4% of organic matter, 30% of water and 66% of inorganic matter; [p] WICEE, 2003; [q] assumed as synthetic rubber from WICEE (2003); [r] Cavalett and Ortega, 2010; [s] Assumed as seeds; [t] Not considered due to lack of material intensity factor; [u] assumed as herbicide from Cavalett and Ortega (2010).

THE SOCIO-ECONOMIC AND BIOPHYSICAL DIMENSIONS OF URBANIZATION STRATEGIES IN RURAL CHINA: LAND USE CHANGES, HUMAN TIME AND ENERGY INTENSITY

Giuseppina Siciliano*

University IUAV of Venice, Research area of "Territory, Economy, and Sustainable Development", Venezia, Italy

ABSTRACT

This paper links development-induced urbanization strategies to changes in land use and associated impacts on rural communities and agro-ecosystems in a selected rural area of China. Energy, monetary and human time variables as well as information on environmental pressures, have been combined to obtain indicators that are useful to compare the metabolism of different patterns of land use from an integrated perspective. The results show that urbanization strategies, aimed at shifting the land use from traditional to monoculture methods and at displacing the local population, while increasing the economic efficiency is also associated with an increase in fossil energy consumption and environmental pressure, as well as a reduction of the multifunctional characteristic of the area under investigation.

Keywords: urbanization, land use change, societal metabolism, agricultural patterns, rural development, China

1. INTRODUCTION

The rapid economic growth of China is driving a fast change in the composition of the society and in particular in the structure of the rural areas. One of the results of this phenomenon is the rapid urbanization of rural people and, consequently, the land-use change of the traditional agricultural systems. According to the latest United Nations population projections, by 2030 almost the 60% of the total population in China will live in urban areas (United Nations, 2005). The causes of the process of urbanization of China can be explained considering two different aspects. On one side, urbanization occurs naturally. People move into cities mostly to seek economic opportunities. On the other side, migration is coming to be considered by Chinese policy-makers as a formal "rural development strategy" (China's 11th Five-Year Plan). As a result, China's modern rural development policy encourages urbanization as one of the main interventions in achieving development goals in rural areas, such as reducing rural-urban gaps in income, poverty and living standards.

The magnitude and the rapidity characterizing the urbanization process in China, have called the attention of the scientific community. At present, a growing number of studies have examined the impacts of urbanization processes on social and ecological systems.

These studies are mainly focused on the social and environmental consequences of fast urbanization in urban areas or on the estimation of the impact of urban sprawl on soil resources (see as an example Ren, 2003; Tan et al., 2005; Xiao, 2006; Chen, 2007; Deng et al., 2009; Liu et al., 2010). However, few studies have analyzed the consequences of urbanization from an integrated perspective and focusing explicitly on rural areas. This paper links development-induced urbanization strategies to changes in land use and the associated impacts on rural people and agro-ecosystems using an integrated assessment

* E-mail: giuseppina.siciliano@gmail.com

approach. This is done by exploring the metabolism of different patterns of land use called for by urbanization interventions in a selected rural area of China. The study aims at answering to the following research questions: What are the socio-economic and environmental consequences of urbanization-induced land use changes in the area of study? In which ways the metabolism of rural systems changes due to urbanization interventions and what are the impacts on the functions and structures of those systems? To answer to the above questions the present paper compares the following land use systems: (1) the current situation, which is represented by a Chinese rural village located in eastern China; and (2) the new rural system resulting from the development-induced urbanization strategy, which aims at shifting the land use of the village into only agricultural land. This intervention will also result in the displacement of the local population from the rural village to the city. The method used to compare the above mentioned systems is the Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) (Giampietro and Mayumi 2000a and 2000b; Giampietro, 2003). The results show that the implementation of the development-induced urbanization strategy analyzed, while increasing the economic efficiency is also associated with an increase in fossil energy consumption and environmental pressure, as well as a reduction of the multifunctional characteristic of the area under investigation.

2. MATERIAL AND METHODS

2.1 Development strategies and land use changes in Hongxing village, China

Hongxing village is located in the eastern part of Chongming island (figure 1). Chongming, with an area of 1,411 km² and a total population of 697,101 inhabitants (Statistical Yearbook, 2007), is the third largest island in China and is administrated by Shanghai's Municipal Government.

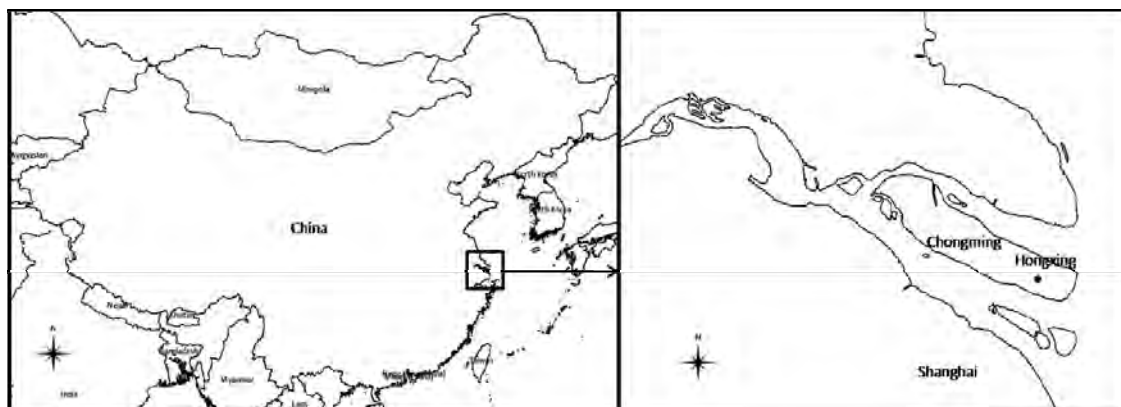


Figure 1. Chongming island and approximate location of Hongxing village

One of the main projects undertaken recently by Shanghai's Municipal Government is the Chongming Island development. The government of Shanghai has developed a comprehensive master plan for the achievement of a sustainable development of the island by the year 2020. The master plan refers to the guidelines of the 11th Five-year Plan for Chongming National Economic and Social Development approved in the 4th Session of the 13th National People's Congress of China (NPC) (The Master Plan of Development of Chongming, 2005-2020) (State Council of China, 2004). Hongxing village will be affected by the development plan through the realization of two main interventions: (i) the diffusion of agricultural areas based on large scale cultivations and monoculture methods; and (ii) the implementation of the "rural-urban migration" strategy related to the gradually integration of the existing rural villages into new denser cities located along the coast.

Based on the above mentioned interventions, this paper analyses and compares the metabolisms of the following rural systems:

- 1) “Business-as-usual (BAU)” system (i.e. Hongxing village). This system supposes that the current land use management does not change over time. The test area is characterized by different land uses, such as human settlements and the agro-ecosystem, and by the realization of traditional agriculture;
- 2) “High input monoculture” system. This system supposes that the land use shifts to only agricultural land. The test area is then characterized by one land use, the agro-ecosystem, and by the realization of monoculture agricultural methods. This system is also associated with the displacement of the local population from Hongxing village to the city.



Figure 2 .Different patterns of land use associated with different patterns of human activities: (a) BAU-Hongxing village; (b) high input monoculture system.

The two systems relate to different patterns of land use (multi-functional versus mono-functional land uses), as well as to different agricultural paradigms (traditional versus mechanized agricultural methods). For traditional agriculture it is considered in this case study a type of agriculture in which no machines are employed, which is defined as “low external power agriculture (LEPA)”. On the contrary, the mechanized agriculture paradigm is based on the extensive use of tractors. This kind of method is defined as “high external power agriculture (HEPA)”. In particular, HEPA is strongly market oriented, tends to be capital-intensive and highly mechanized. On the contrary, LEPA is realized prevalently for subsistence purposes, it is based on manual work instead of the use of machines. Therefore, it results less capital-intensive than HEPA. Figure 2 visualizes the land use changes in Hongxing village that will occur under the Master Plan of Development of Chongming, and table 1 gives an overview of their main characteristics.

Table 1 Overview of the alternative land-use systems

Scenarios	Main characteristics
BAU Hongxing village	• Multi-functional land use: human settlements (local communities), aquaculture, and agriculture (agro-ecosystems) • LEPA - Low External Power Agriculture: low capital-intensive, weakly market oriented (mostly subsistence agriculture), no mechanized • Conventional agricultural methods: no reduction of inputs in terms of fertilizers and pesticides • Reproducing local communities: system characterized by the presence of a variety of work patterns (on-farm, off-farm and partially off-farm household

	typologies)
High input monoculture	• Mono-functional land use: agriculture (only agro-ecosystem) • HEPA – High External Power Agriculture: strongly market oriented, capital-intensive, highly mechanized. • Conventional agricultural methods: no reduction of inputs in terms of fertilizers and pesticides • Non-reproducing local communities: system characterized by the presence of only agrarian seasonal work (mainly hired work from retired people)

2.2 Method

The Multiple-Scale Integrated Analysis of Societal and Ecosystem Metabolisms (MuSIASEM) has been introduced by Giampietro and Mayumi in 2000 (Giampietro and Mayumi, 2000a and 2000b) and subsequently formulated by Giampietro (2003). The MuSIASEM approach has been developed as a framework for the integrated assessment of sustainability issues. According to the MuSIASEM approach social systems (i.e. a country, a village, a household, an individual) are viewed as complex adaptive systems (CAS)² operating on different hierarchical levels and dimensions of analysis (economic, environmental and social). The multi-scale and multidimensional aspects of social systems, makes it necessary the use of integrated assessments able to examine them by applying in parallel a “socio-economic reading” and a “biophysical reading” and considering also different scales of analysis.

The basic principles of the MuSIASEM approach can be found in the concept of “societal and ecosystem metabolism” and the Georgescu Roegen’s fund-flow model (Georgescu-Roegen, 1972; 1975). The concept of “societal and ecosystem metabolism” is used to represent the processes of energy and material transformation in a society that are necessary for its continued existence (Martinez-Alier and Schlüpmann, 1987; Ayres and Simonis, 1994; Fischer-Kowalski, 1998; Giampietro et al., 2009). Based on these processes, the MuSIASEM approach establishes a representation of the performance of social systems by using a series of variables, referring to (1) the biophysical characteristics of the system, such as energy and land use, and (2) the socio-economic characteristics, such as human time and monetary variables. The analysis of the relationships among economic information, demographic information (represented by the human time) and biophysical information (represented by energy and land use), gives the possibility to have an integrated representation of social systems.

According to the fund-flow model, when studying a CAS in terms of both the interaction of the system with its external context and the description of its main characteristics, two different categories of elements have to be considered: flow and fund categories (Georgescu-Roegen, 1975). Flow categories are “elements that enter but do not leave the process, or conversely, elements that exit without having entered the process”, such as for example energy, matter, money, information, while funds refer to “elements that enter and exit the process unchanged” (Mayumi and Gowdy, 1999; Giampietro et al., 2009), such as human time, land or the number of people. In other words, funds and flows are all the variables and factors that describe the interaction among the system and the economic and environmental contexts embedding the system itself. By adopting this approach CAS can be represented as metabolic systems characterized by the exchange of inputs (e.g. energy, food, money, information), i.e. the flow elements, and by a given structure represented by fund elements (e.g. the size of the system expressed by time, land, people, capital).

² For a detailed explanation of the main characteristics of CAS see Koestler, 1967; Allen and Starr, 1982; Salthe, 1985; Holland, 1995; Levin, 2000.

2.2.1 Representation of the rural systems using fund and flow variables

In this section the MuSIASEM approach has been applied to the analysis of the two rural systems described in section 2.1, figure 2 and table 1. The two systems under investigation are described based on the following variables: human time, land use, monetary flow and energy flow. These variables allow representing both systems taking into account simultaneously a “socio-economic reading” and a “biophysical reading”. The graphs of Fig. 3 show the possibility of using the fund-flow model adopted by the MuSIASEM approach to describe the metabolisms of the two patterns of land use under investigation, based on the parallel representation of fund (human activity and land use) and flow variables (monetary and energy flows).

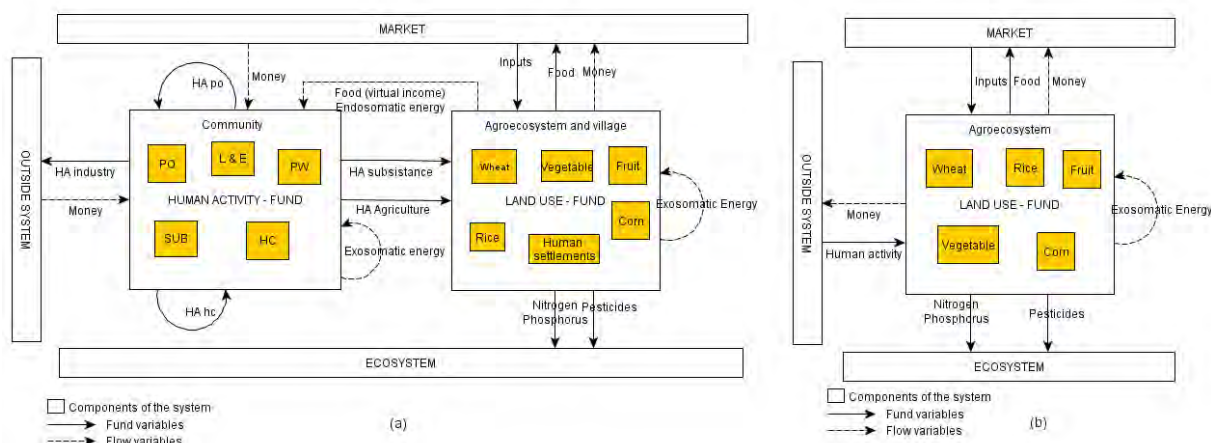


Figure 3 Representation of the systems using fund and flow variables: (a) BAU, Hongxing village; (b) High input monoculture system

The Hongxing village system, part (a) of figure 3, consists of the following components: (1) the community, i.e. the society represented by the fund human activity (hours of human activity: physiological overhead – PO, leisure and education – L&E, paid work – PW, subsistence – SUB, household chores – HC) and (2) the agro-ecosystem and the village expressed by the fund land use (agriculture, human settlements). On the contrary, the high input monoculture system, part (b) of figure 3, consists of the agro-ecosystem only, where the use of the time is represented by the hours dedicated only to the paid work sector. The arrows represent the interaction between the components of the systems (community and agro-ecosystem) and between the systems and the external socio-economic and environmental contexts (respectively outside the system, market and ecosystem). In particular, the systems interact with the external contexts through the exchange of money, food, inputs of production and hours of human activity. At the same time they release in the ecosystem substances derived by the process of production (in this case by the use of fertilizers and pesticides). Finally, all the activities realized within the systems are sustained by the consumption of energy (i.e. exosomatic energy³). The peculiar characteristic of this approach is that it addresses explicitly the relation between the two fund elements: (1) human activity (characterized by the size of the community in terms of hours of human activity); and (2) land use (expressed in hectares), as well as the flow elements considered: (i) monetary flows; (ii) flows of fertilizers and pesticides; and (iii) exosomatic energy. The representation and quantification of the fund and flow variables described above makes it possible to derive and evaluate multidimensional indicators, which represent the societal and ecosystem metabolisms of the systems compared (for a detailed description of the indicators see table 2).

³ Exosomatic energy is generated by transforming energy outside of the human body, such as burning gasoline in a tractor for the production of food (i.e. agricultural products).

Table 2. Description of the indicators of performance

Dimensions and criteria		Unit	Description
Economic dimension			
1)	Labor Productivity	RMB ^b /hour	Monetary flow generated per hour of work (comprising also the “virtual income”)
2)	Monetary flow	t.RMB/ha/year	Gross income generated by the working activities in a year
Social dimension			
3)	Working time	hour ha ⁻¹ year ⁻¹	Time dedicated by the local population to working activities
4)	Non-working time	hour ha ⁻¹ year ⁻¹	Time dedicated by the local population to non-working activities
5)	Diversification of risk	Qualitative	Qualitative evaluation based on the fractions (%) of the monetary flow generated by on-farm and off-farm activities
Environmental dimension			
6)	Use of pesticides	Kg ha ⁻¹ year ⁻¹	Amount of chemical pesticides utilized in agriculture per unit of land in a year
7)	Nitrogen use	Kg ha ⁻¹ year ⁻¹	Amount of nitrogen utilized in agriculture per unit of land in a year
8)	Energy intensity	MJ/ha/year	Energy flow per unit of land

^bRMB-Renminbi (people's money) is the Chinese currency.

By developing this integrated analysis it becomes possible to understand how changes in the pattern of human activity (associated with changes in the pattern of production, i.e. traditional versus monoculture practices) are reflected into changes in the pattern of land use. In particular, in the application of this approach to the metabolic pattern of Hongxing village it is possible to observe the clear discontinuity in the pattern of land use determined by the switch to the high input monoculture production– on the right of Fig. 2 and Fig.3 – compared with the traditional pattern - on the left of Fig. 2 and Fig.3.

3. DATA COLLECTION

Data, used for the final evaluation of the indicators, have been collected during a field work realized between October 2008 and January 2009 in Hongxing village, by the use of questionnaires submitted to: a sample of 104 households (representing approximately the 10% of the total number of households in the village), the head of the village and agricultural technicians. Information collected from the households has been then used to estimate the data at the level of the village (the table in the appendix shows all data collected at the household level).

4. RESULTS

In this section the comparison of the metabolism of the different land use patterns is realized based on the use of the variables human time, energy flow and monetary flow, such as explained in section 2.2. Table 3 shows the final estimation of the human time variable with respect to different human activities (working and non working activities) as well as the estimation of the energy and monetary flows per each land use pattern.

Table 3. Energy flow, human time and monetary flow

	Energy flow (MJ/year)	Total Human time (hours/year)	Working time (hours/year)	Non working time (hours/year)	Monetary flow (t.RMB/year)
BAU – Hongxing village	12,476,000	20,550,233	4,857,030	15,693,203	24,528
High input monoculture system	71,767,789	138,509	138,509	0	6,348

Table 4. Indicators of performance

Indicators	Unit of measurement	BAU Hongxing village	High input monoculture system
Energy intensity	MJ/ha/year	28,947	166,515
Labor productivity	RMB/hour/year	5.05	45
Working time	hour ha ⁻¹ year ⁻¹	11,269	321
Non working time	hour ha ⁻¹ year ⁻¹	46,021	0
Use of pesticides	kg ha ⁻¹ year ⁻¹	5.4	7.8
Use of nitrogen	kg ha ⁻¹ year ⁻¹	219	291
Diversification of risk	Qualitative	high	low

The data of table 3 are used to evaluate the indicators energy intensity⁴, monetary flow per unit of land (i.e. gross income per hectares), labor productivity, diversification of risk⁵ and the human time used with respect to working and non working activities. Moreover, two other indicators of environmental performance are taken into account. They refer to the use of pesticides and fertilizers per unit of land (table 4).

Based on the above results, the high input monoculture system with respect to Hongxing village is associated with:

- An increase of the energy intensity, which means more fossil energy consumed per unit of land;
- An increase of the economic efficiency in terms of the monetary flow per hour of work (i.e. labor productivity);
- A reduction of the total working hours and the disappearance of the human time dedicated to non working activities, which explains the displacement of the rural communities from the area of study to the city;
- An increase of the environmental pressure on the soil resource, expressed by the higher use of pesticides and fertilizers.
- A reduction of the diversification of risk, which means less diversification of the activities performed with respect to the BAU system (i.e. only agricultural activities).

Therefore, it is clear that the adoption of HEPA patterns together with forced rural-urban migration implies the abandonment of integrated rural realities in favor of simplified agricultural systems. These systems are linked to a change of the structure of the area

⁴ The evaluation of the energy intensity has been based on information related to the type, weight and horse power of the tractors and the fertilizer and pesticides used (the conversion factors used to assess the energy equivalents of inputs in the agricultural sector are those indicated in Giampietro, 2002). In the case of the BAU system the energy consumption related to housing, i.e. personal care, leisure, house working has been also taken into consideration.

⁵ The indicator “diversification of risk” has been evaluated qualitatively based on the analysis of the fractions of the income generated by off-farm and on-farm activities. Higher is the balance between the two percentage values obtained, higher is the diversification of risk attached to the systems (detailed information regarding the methods used to evaluate this indicator will be given by the author upon request).

under investigation in terms of land uses and human time, as well as to a change of their function. The main function of the HEPA pattern is the production of agricultural products to be sold in markets in cities (mainly to feed the increasing population of the big cities, such as Shanghai). On the contrary, in the LEPA system the food production is mainly used to sustain the food requirement of the local population. In other words, the high input monoculture system is a system in which the maximization of the economic efficiency, expressed by the monetary flow per hour of work, is not functional to the reproduction of the fund human activity, which represents the local rural communities; instead it focuses on how to optimize the generation of the monetary flows. The results show that this economic efficiency can only be achieved through: the displacement of the rural communities from sparsely-located villages to concentrated cities; an increase of the environmental pressures (more fertilizers and pesticides used); an increase of the consumption of fossil fuels per unit of land; and finally a simplification of the functional characteristics of rural systems, i.e. less diversification of the activities performed.

5. DISCUSSION AND CONCLUDING REMARKS

The analysis of the environmental and socio-economic effects of urbanization processes has recently received much attention, especially in China. However, detailed analyses of the effects of development-induced urbanization processes on rural people and rural ecosystems are still missing. While there is plenty of evidence of the consequences of the land use change due to the expansion of cities, more systematic evaluations are needed to understand how the rural land use changes, due to forced rural-urban migration, and what are the impacts of this change on rural ecosystems and communities. Drawing on own data, collected during a field work of four months, this paper has analyzed the potential effects of development-induced urbanization strategies on the structure and function of a rural village located in eastern China from a multidimensional integrated perspective. Energy, monetary and human time variables as well as information on environmental pressures, have been combined to obtain indicators that are useful to compare the societal and ecosystem metabolism of different patterns of land use. This approach makes it possible to explore the complexities of some of the relevant socio-economic and biophysical aspects of urbanization policy impacts and trade-offs. The study illustrates how forced urbanization could drive the transformation of rural land use systems and how this change affects agro-ecosystems and rural communities. The results have showed that the development-induced land use change analyzed, while improving the efficiency of the rural economy, it leads to higher environmental stress, higher consumption of fossil energy, as well as less diversification of the activities performed in the area of study. In other words, the rural transformation analyzed here is associated with a major simplification of the functional and structural organization of traditional agro-ecosystems. That is, it requires the abandonment of multifunctional systems that are useful for guarantying to the rural community a high level of diversification of risk and food-self sufficiency. These considerations question the effectiveness of the development-induced urbanization strategies here analyzed and underline the importance of seeking for alternative development solutions to improve the livelihood of the rural population and the protection of the rural ecosystems. With respect to future policy development, closer attention should be paid to local solutions. The income level of the rural population is still too low in most of the rural areas of China. The table in the appendix shows an income level of the on-farm household types in Hongxing village of approximately 11.000 RMB per year, which is extremely low if compared to the income of the off-farm types with approximately 37.000 RMB/year. However, this study demonstrates that the forced migration of rural people to cities cannot be considered a sustainable development strategy. Instead, innovative solutions, based for instance on seeking for a good balance between off-farm and on-farm activities, should be explored in order to guarantee a sustainable development in rural areas and avoid increasing environmental pressures on rural ecosystems.

ACKNOWLEDGEMENTS

I would like to acknowledge Prof. Mario Giampietro from the Institute of Environmental Science and Technology (ICTA) of the Universidad Autonoma de Barcelona for helpful comments. I would also like to thank all Chinese farmers, agricultural technicians, and the head of Hongxing village, who were involved in the collection of data. Finally, I thank very much Prof. Genxiang Shen and Mya Guhr from the Shanghai Academy of Environmental Sciences (SAES), Prof. Maria Lodovia Gullino and Massimo Pugliese from Agroinnova for the scientific and technical support and helpful discussions.

REFERENCES

- Allen, T. F. H. & Starr, T. B. 1982. *Hierarchy: Perspectives in Ecological Complexity*. University of Chicago Press, Chicago, London
- Ayres, R.U., Simonis, U.E. 1994. *Industrial Metabolism: Restructuring for Sustainable Development*. United Nations University Press, Tokyo, 376 pp.
- Chen, Jie. 2007. "Rapid urbanization in China: A real challenge to soil protection and food security". *CATENA* 69, 1-15.
- China's 11th Five-Year Plan for National Economy and Social Development. Retrieved from: http://www.china.org.cn/features/guideline/node_1156529.htm (05-12-2010)
- Deng, J. S., Wang K., Hong Y., and Jia G. Qi. 2009. "Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization". *Landscape and Urban Planning* 92, no. 3-4, 187-198.
- Fischer-Kowalski, M. 1998. "Society's metabolism. The intellectual history of material flow analysis, Part I: 1860–1970". *Journal of Industrial Ecology*, 2, 61–78
- Georgescu-Roegen, N., 1971. *The Entropy Law and the Economic Process*. Harvard University Press, Harvard, 457 pp.
- Georgescu-Roegen, N. 1975. "Energy and economic myths", *South Econ J*, 41, 347–381
- Giampietro, M. 2002. *Energy use in agriculture*, *Encyclopedia of Life Sciences*, Macmillan Publishers, Nature Publishing Group
- Giampietro, M. 2003. *Multi-scale integrated analysis of agro ecosystems*. CRC Press, New York, 474 pp.
- Giampietro, M., and Mayumi k. 2000a. "Multiple-scale integrated assessment of societal metabolism: introducing the approach", *Population and Environment*, 22 (2), 109-153.
- Giampietro, M., and Mayumi K. 2000b. "Multiple-scale integrated assessment of societal metabolism: integrating biophysical and economic representations across scales", *Population and Environment*, 22 (2), 155-210
- Giampietro M., Mayumi K., Ramos-Martin J., 2009. "Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM): Theoretical concepts and basic rationale", *Energy*, vol. 34/3, 313-322
- Holland, J. H., 1995. *Hidden order. How adaptation builds complexity*, Helix Books, 185 pp.
- Koestler, A. 1967. *The ghost in the machine*. Macmillan, New York
- Levin, S.A. 1999. *Fragile Dominion: Complexity and the Commons*. Helix Books/Perseus Publishing, 256 pp.
- Liu Y., He S., Wu F., Webster C. 2010. "Urban villages under China's rapid urbanization: Unregulated assets and transitional neighborhoods", *Habitat International* 34, 135–144
- Martínez Alier, J., Schlüpmann, K., 1987. "Ecological economics: energy". In: *Environment and Society*. Basil Blackwell, Oxford, 286 pp.
- Mayumi, K., Gowdy, M. 1999. *Bioeconomics and Sustainability. Essays in honor of Nicholas Georgescu-Roegen*, Edward Elgar, Massachusetts, USA, 403 pp.
- Ren, W., Zhong Y., Meligrana J., Anderson B., Watt W. E., Chen Ji., e Leung H. 2003. "Urbanization, land use, and water quality in Shanghai: 1947-1996". *Environment International*, 29, no. 5, 649-659.
- Salthe, S. 1985. *Evolving Hierarchical Systems: their structure and representation*. Columbia University Press, New York
- United Nations, 2005. *World Urbanization Prospects. The 2005 Revision*, Department of Economic and Social Affairs, Population Division, New York
- Statistical Yearbook, 2007. *Shanghai Statistical Yearbook 2007*, Shanghai, China. English version. Retrieved from: <http://www.stats-sh.gov.cn/2004shtj/tjnj/tjn2007e.htm> (04-10-2010)

- State Council of China, 2004. The Master Plan of Development of Chongming. English version. Retrieved from: <http://www.cmx.gov.cn/gb/node2/node21/node22/index.html> (04-10-2010)
- Tan, M., Li X., Xie H., and Lu C. 2005. Urban land expansion and arable land loss in China - A case study of Beijing-Tianjin-Hebei region. *Land Use Policy*, 22, no. 3, 187-196
- Xiao, J., Shen Y., Ge J., Tateishi R., Tang C., Liang Y., and Huang Z. 2006. Evaluating urban expansion and land use change in Shijiazhuang, China, by using GIS and remote sensing. *Landscape and Urban Planning*, 75, no. 1-2, 69-80.

Appendix

Table 1 Data collected at the household level in Hongxing village and aggregated in three different classes of households: off-farm, on-farm, and partially off-farm.

Variables	Off-farm	On-farm	Partially off-farm
Number of observations	35	21	29
HH size (average No. of members)	2.95	2.00	2.40
THA - Total Human Activity (hours per year)	25,842	17,520	21,024
<i>Working hours (%)</i>			
Agriculture	-	14.80	12.18
Industry	14.80	-	3.67
Trade & Services	8.14	-	-
Aquaculture	-	-	-
Husbandry	-	2.92	-
Others	-	-	3.58
Households' chores	8.98	8.72	9.63
<i>Non working hours (%)</i>			
Physiological overhead	45.37	48.80	44.28
Leisure & education	23.00	26.43	25.69
Total income, including virtual income^a (RMB/year)	37,004	10,914	17,292
<i>On farm (%)</i>			
Agriculture	-	79.94	56.26
Aquaculture	-	-	-
Husbandry	-	8.00	0.30
<i>Off-farm (%)</i>			
Industry	70.21	-	24.60
Trade & Services	29.79	-	-
Others (%)	-	12.08	18.84
Expenditures (RMB/year)	15,849	5,005	8,466
Total Available Land (ha)	0.03	0.85	1.19
<i>Land use (ha)</i>			
House area	0.01	0.01	0.01
Homestead area	0.02	0.01	0.02
Agricultural area	-	0.41	0.58
Energy consumption			
Electricity (kW/month)	45.90	24.35	35.60
Liquefied gas (kg/month)	14.80	20.75	13.77
Fuel (liter/month)	6.55	0.15	0.97
Firewood (kg/month)	-	69.15	8.33

^a The “virtual income” voice has been evaluated based on the information collected at the household level related to the fraction of the various agricultural products auto-consumed by the household and their average market prices.

ALTERNATIVE ENERGY SOURCES: INTEGRATING URBAN WASTEWATER TREATMENT AND WOOD BIOMASS PRODUCTION FOR BIOENERGY PURPOSE

Elvira Buonocore^{*1}, Pier Paolo Franzese, Sergio Ulgiati

Department of Environmental Sciences, Parthenope University of Naples,
Naples, Italy

ABSTRACT

Bioenergy, defined as the energy extracted from organic matter (biomass), has recently become one of the most dynamic and rapidly changing sectors of the global energy economy. The use of food crops for conversion to biofuel has been criticized for several reasons, among which its competition with the global food chain. Instead, lignocellulosic substrates are claimed to provide a bioenergy alternative without competing with food demand. This is particularly true when dealing with residues or waste. In this paper we explore the environmental performance and sustainability of an integrated bioenergy production system located in the municipality of Enköping (Sweden). The methodology used to perform the study was the "Sustainability Multi-method Multi-scale Approach" (SUMMA). Actual data from the integrated bioenergy production system were collected during a previous research carried out in collaboration with the Department of Urban and Rural Development of the Swedish University of Agricultural Sciences (SLU). The investigated system integrates wastewater treatment, willow biomass cropping, and energy production. The willow cropping system coupled with the biological treatment of nutrient-rich municipal wastewater leads to a substantial biomass yield increase, a reduced use of fertilizers, and a lower pollution of groundwater, generating at the same time notable savings of resources for wastewater treatment. The willow biomass as well as logging residues and waste from wood and paper industries is then combusted within a Combined Heat and Power Plant (CHP-plant) for cogeneration of heat and electricity supplying the municipality of Enköping. Upstream and downstream indicators were calculated for the intermediate systems of the integrated process and CHP plant. Results show that proper short rotation forestry and use of wood residues can improve the performance and sustainability of energy production, especially when integrated to wastewater treatment. Finally, three scenarios were drawn to assess the variation of such indicators according to different transportation distances.

Keywords: Bioenergy, Sweden, SUMMA, Multi-criteria assessment

1. INTRODUCTION

Bioenergy has become a critical priority worldwide mainly due to growing concerns about environmental impacts associated with the use of fossil fuels, national energy security, sustainability of natural resources, and the need to revitalize rural economies (Volk *et al.*, 2004). Conversion of forest and agricultural residues to charcoal as well as district and home heating are the most common forms of bioenergy. Biomass feedstocks for electricity generation are predominantly forest and agricultural residues (Wright, 2006). In particular, there has been an increasing interest in developing short rotation woody crops due to multiple environmental, rural, and social benefits associated with their production and use.

Since the oil crises in the 1970's, substantial efforts have been made in Sweden to improve short-rotation forest production for wood fuel generation (Rosenqvist *et al.*, 2000).

About 16,000 ha of willow in short rotation coppice systems (mainly consisting of different clones and hybrids of *Salix viminalis*, *Salix dasyclados*, and *Salix schwerinii*) are

* Corresponding author; E-mail: elvira.buonocore@uniparthenope.it

currently grown in Sweden (Dimitriou and Aronsson, 2004). Willow has several features that make it ideal for woody crop systems, including high yields obtained in a few years, an easy vegetative propagation, a broad genetic base and the ability to resprout after multiple harvests. Short rotation willow coppice is also used for wastewater treatment, as a complement to conventional treatment. Indeed, as a vegetation filter, the willow has a good ability to take up nutrients from wastewater. The average nutrient content in Swedish municipal wastewater meets the requirement of willow for nitrogen (N) and phosphorus (P), avoiding the need for additional commercial fertilizers (Börjersson and Berndes, 2006).

According to the so-called “zero-emission” production patterns, waste generated by a process are used as inputs to supply another production pattern. Instead, within a conventional (linear) production pattern resources are processed while waste are merely released to the environment. As a consequence, energy and material cost of the product is higher, the efficiency of the process is lower, and higher emissions are released in the environment (Ulgiati *et al.*, 2006).

The town of Enköping in Sweden has a pioneering bioenergy production system (McCormick and Kaberger, 2005) integrating wastewater treatment, willow cropping, and heat and electricity production. The willow cropping system is coupled with the biological treatment of nutrient-rich municipal wastewater; wastewater application leads to a substantial biomass yield increase, a reduced use of fertilizers, and a lower pollution of groundwater.

A Combined Heat and Power plant (CHP plant) uses the produced willow biomass for the cogeneration of heat and electricity supplied to the municipality of Enköping.

In this paper, the “Sustainability Multimethod Multiscale Assessment - SUMMA - (Ulgiati *et al.*, 2006) was used to explore the environmental performance and sustainability of the Enköping bioenergy production plant and its three subsystems: 1) wastewater treatment, 2) willow farming, and 3) heat and electricity cogeneration. The final goal of the paper was to carry out a comprehensive and multicriteria set of indicators able to explore different features of the investigated systems: use of matter, energy, and money flows, rate of local resources use versus imported, rate of renewable resources use versus non-renewable, interplay between socio-economic dynamics and natural ecosystems.

2. MATERIALS AND METHODS

2.1 The Enköping bioenergy production system

Enköping is a town in central Sweden with about 20,000 inhabitants. It is located in a densely populated region where several towns are supplied by district-heating systems based on biomass. Enköping’s municipality developed several strategies to utilize willow plantations for purifying wastewater coming from both private septic tanks and municipal wastewater treatment plant.

The investigated farmland, named “Lundby Gård”, comprises 100 ha of willow plantation used as a vegetation filter for wastewater treatment. Sludge from septic tanks is transported and pumped by trucks into storage ponds where it rests for one year to reduce its microbial charge. Afterwards, during the summer (May to September) for about 120 days per year, the sludge is spread over the willow plantations through an irrigation system. Since willow root systems can take up 75-95% of nitrogen and phosphorus in the wastewater, the annual wastewater load can easily supply both the requirements in terms of water, nitrogen, and other macronutrients. Moreover, the irrigation with nutrient-rich water promotes plant growth resulting in higher biomass harvests: wastewater irrigation is estimated to increase the yields by 30% compared to the conventional plantations (Börjersson and Berndes, 2006).

Willow is harvested in winter every 3-5 years; after the harvest, the plants coppice vigorously, and replanting is therefore not necessary for a period of 20-25 years.

The willow biomass produced is transported and burned in the *Ena Energi* CHP plant, located in Enköping. Established in 1994 and mainly based on biofuels, the CHP plant cogenerates electricity for sale on the Nord Pool market, including Sweden, Norway, Denmark and Finland. The heat is delivered by means of district heating to almost all the buildings of the town.

A variety of biomass is used in the CHP plant, including willow, residues from wood industries, agricultural wastes, and forest residues. The willow production in the city of Enköping provides 15-20% of the total biomass combusted. Most of the biomass is not available in the surrounding area and it is imported from forestry (typical trucking distance 90 km) and wood industries (typical trucking distance 200 km).

Combustion is made with wood-fuels during the whole year; the strategy is to burn wood biomass in the period April-October with a supply of willow during the winter period (November-March). The boiler generates 24 MW of electricity and 45 MW of heat, supplying 50% of the electricity demand and 85% of the heat demand of the municipality of Enköping.

2.2 SUsustainability Multimethod Multiscale Assessment (SUMMA)

The methodological framework used in this study is the “SUsustainability Multimethod Multiscale Assessment” (SUMMA) (Ulgiati *et al.*, 2006). SUMMA is a platform for an extended life cycle assessment (LCA), where several evaluation methods are used to provide a set of complementary indicators at multiple scales, based on the same set of input data.

The investigated system or process is treated as a “black box” and an inventory of all the input and output flows is firstly performed on its local scale; this inventory forms the common basis for all subsequent impact assessments, which are carried out in parallel in order to ensure the maximum consistency of basic assumptions and input data. The assessment methods can be divided in two broad categories: 1) those based on the amount of resources used per unit of generated product (“upstream” methods), 2) those based on the consequences of the system’s emissions (“downstream” methods). The upstream methods are concerned with the inputs and they account for the depletion of environmental resources. On the other hand, the downstream methods focus on the environmental consequences of the emissions and they are related to the perceived impact on local ecosystem.

2.2.1 Upstream methods and indicators

The **Material Flow Accounting** method (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998; Bargigli *et al.*, 2005) is aimed at evaluating the environmental disturbance associated with the withdrawal or diversion of material flows from their natural ecosystemic pathways.

In this method, appropriate material intensity factors (g/unit) are multiplied by each input to the process to account for the total amount of biotic and abiotic matter, water, and air, directly or indirectly required to support the process. The resulting material demands aggregated for each environmental compartment (biotic and abiotic matter, water, air) are then assigned to the system’s output as a quantitative measure of its cumulative environmental burden from that compartment.

The **Embodied Energy Analysis** method (IFIAS, 1974; Herendeen, 1998, Franzese *et al.*, 2009) is aimed at evaluating the direct and indirect requirements in terms of fossil fuels (sometimes also referred to as commercial energy).

In this method, all the material and energy inputs to the process are multiplied by appropriate oil equivalent factors (g of oil equivalent / g of input); the cumulative energy requirement of the system’s output is then calculated as the sum of the oil equivalents of

the inputs. The so-called “Gross Energy Requirement” (GER) indicator expresses the total of commercial energy required per unit of output.

The **Emergy Accounting** method (Odum, 1988, 1996; Brown and Ulgiati, 2004) is aimed at evaluating the environmental performance of the system on a global scale, also taking into account the free environmental inputs (for instance, sunlight, wind, and rain) as well as the indirect environmental support embodied in human labor and services, usually not included within conventional energy analyses (Franzese *et al.*, 2009).

In this method, all inputs are accounted for in terms of their solar emergy, defined as the total amount of solar available energy (exergy) directly or indirectly required to make a given product or support a given flow, and measured as solar equivalent joules - seJ - (Odum, 1996). The amount of emergy that is required to generate one unit of each input is referred to as its specific emergy (seJ/unit) in case of mass flows and solar transformity (seJ/J) in case of energy flows. Such emergy intensity factors can be considered a “quality” factor accounting for the environmental support provided by the biosphere to the formation of each input. Finally, the specific emergy or transformity of the system’s output is calculated as the ratio between the total emergy used up by the process and the system’s output expressed in terms of mass or energy (Odum, 1996).

2.2.2 Downstream methods and indicators

The **CML2 baseline 2000** (Centre of Environmental Science, Leiden University, NL, 2000) method is aimed at evaluating a set of crucial downstream impacts; it calculates the potential environmental damage of airborne, liquid, and solid emissions by means of appropriate equivalence factors to selected reference compounds for each impact category. The potential impact of the investigated process for each category is calculated by multiplying all the emissions by their respective impact equivalence factors.

The impact categories are:

- Global warming potential (carbon footprint)*, expressed in grams of CO₂ equivalent per gram of product;
- Acidification potential*, expressed in grams of SO₂ equivalent per gram of product;
- *Eutrophication potential*, expressed in grams of PO₄⁻³ equivalent per gram of product;
- Tropospheric ozone and photosmog formation potential*, expressed in grams of ethene equivalent per gram of product;
- Stratospheric ozone depletion potential*, expressed in grams of CFC-11 equivalent per gram of product;
- Ecotoxicity potential*, expressed in grams of 1,4-dichlorobenzene equivalent per gram of product.

3. RESULTS AND DISCUSSION

3.1 Material Flow Accounting

Table 1 shows intensive and extensive indicators of Abiotic Material Requirement calculated for the CHP plant. The same indicators were calculated for the intermediate systems of wastewater treatment and willow farming.

Extensive indicators account for the total flows supporting the system, including also hidden flows occurring at larger spatial and time scales. Of course, extensive indicators are directly related to the physical size of the system and a variety of factors such as technological improvement or price. Indeed, such factors may affect the modality of use of some input flows. On the other hand, intensive indicators are relatively independent on the physical size and provide a measure of efficiency (performance) with relation to the final product (e.g., more or less material or energy used per unit of product or per unit of time).

The total abiotic demand ($2.49 \cdot 10^{10}$ g/yr) and the total water demand ($5.30 \cdot 10^{11}$ g/yr) do not only include the direct abiotic material and water supply on the investigated period, but also the indirect supply over the LCA chain of input flows.

The abiotic material intensity of electricity resulted 69.21g/MJ; the average abiotic material intensity calculated for electricity generated in the European countries is equal to 478 g/MJ (Wuppertal Institute, 2009). The lower indicator for the electricity based on wood biomass reveals a higher efficiency in resource consumption compared to the average value for electricity production in Europe. Global to local ratios explain the relation between the process occurred locally and other processes occurred globally but providing input to the local system. The global to local ratio of water demand was 15.14 (Table 1) and it highlights the remarkable amount of water used globally to support the local production of electricity.

Table 1. Material Flow Accounting indicators of the CHP plant.

Material Flow Accounting	Value	Unit
Intensive Indicators		
Abiotic Material Intensity per MJ of electricity	69.21	g/MJ
Abiotic Material Intensity per MJ of heat	34.60	g/MJ
Water Demand per MJ of electricity	1471.52	g/MJ
Water Demand per MJ of heat	735.76	g/MJ
Total Material Intensity per MJ of electricity	1540.73	g/MJ
Total Material Intensity per MJ of heat	770.36	g/MJ
Global to local ratio of abiotic material	0.43	
Global to local ratio of water demand	15.14	
Extensive Indicators		
Total Abiotic Material Requirement	2.49E+10	g/yr
Total Water Demand	5.30E+11	g/yr

3.2 Embodied Energy Analysis

Quantifying the total energy invested into a process allows an estimate of the total amount of primary energy use and, as a consequence, of the non renewable energy sources depleted due to the process.

In Table 2 the energy indicators calculated for the CHP plant are summarized. The embodied energy per unit of electricity and heat resulted 0.27 and 0.07 MJ/MJ, respectively. The oil equivalent intensities per unit of electricity and heat resulted 6.37 and 1.59 g_{oil}/MJ, respectively. These indicators were calculated by accounting for the ability of the final products to do useful work (exergy). In so doing, the total embodied energy applied ($1.44 \cdot 10^8$ MJ/year) and the total oil equivalent applied ($3.44 \cdot 10^9$ g_{oil}/yr) were allocated to the exergy of the heat and electricity generated per year.

The Energy Return On Investment (EROI) was evaluated by dividing the energy content of the products by the amount of fossil energy invested to produce them. The EROI of electricity generation ranges from a low 0.30 of an oil-powered plant to the high 23.7 of an hydroelectric plant (Brown and Ulgiati, 2004). The value of 9.37 calculated for the CHP plant is comparable with other technologies relying on renewable sources, such as hydro or wind power (Brown and Ulgiati, 2004).

3.3 Energy Accounting

The results obtained from the application of Emergy Synthesis to the CHP plant are shown in Table 3.

The solar transformity calculated for the electricity produced from biomass combustion resulted $1.21 \cdot 10^5$ seJ/J; this value falls in a range of transformities calculated for electricity produced by other sources such as methane, solar, and geothermal, ranking from $1.1 \cdot 10^5$ to $3.5 \cdot 10^5$ seJ/J (Brown and Ulgiati, 2004).

The renewable fraction for electricity from biomass resulted 0.31. This indicator is higher than other fossil fuels-based electricity productions (characterized by a range of

0.06-0.08) but still lower than the electricity generated by wind, geothermal and hydro plants, showing a range of 0.68-0.86 (Brown and Ulgiati, 2002). Such an outcome can be explained by considering that the biomass sources feeding the plant cannot be fully considered a renewable source as fossil fuels are directly and indirectly required by forestry, agricultural, and industrial activities as well as for the transportation of the biomass to the CHP plant. Moreover, such plant strongly depends on both non renewable material and energy flows as well as labor and services (in turn supported from external non renewable inputs). For this reason, the Environmental Loading ratio (ELR) resulted 2.20 and the Emergy Yield Ratio (EYR) was close to 1 (Table 3) like in the case of other fossil fuel-based technologies (Brown and Ulgiati, 2004). The Emergy Sustainability Index (ESI) for the CHP plant resulted 0.47.

Table 2. Gross Energy Requirement indicators of the CHP plant.

Gross Energy Requirement	Value	Unit
Intensive Indicators		
Oil equivalent intensity per MJ of electricity	6.37	g_{oil}/MJ
Oil equivalent intensity per MJ of heat	1.59	g_{oil}/MJ
Embodied energy per MJ of electricity	0.27	MJ/MJ
Embodied energy per MJ of heat	0.07	MJ/MJ
EROI of products	11.25	
EROI of electricity	9.37	
EROI of heat	14.99	
Global to local energy ratio	1.12	
Extensive Indicators		
Total embodied energy applied	1.44E+08	MJ/yr
Total oil equivalent applied	3.44E+09	g_{oil}/yr

Table 3. Emergy based indicators of the CHP plant.

Emergy accounting	Value	Unit
Intensive Indicators		
Transformity of electricity	1.21E+05	seJ/J
Transformity of heat	6.07E+04	seJ/J
Emergy from local resources, (R+N)/U	3.91E-02	
Emergy from renewable resources, R/U	1.36E-02	
Emergy from imported resources, F/U	0.96	
Renewable fraction, REN%	0.31	
Environmental Loading Ratio, (ELR) = (F+N)/F	2.20	
Emergy Yield Ratio, (EYR)=(R+N+F)/F	1.04	
Emergy Sustainability Index, (ESI)=EYR/ELR	0.47	
Extensive Indicators		
Emergy from local renewable resources, R	5.93E+17	seJ/yr
Emergy from local non renewable resources, N	1.12E+18	seJ/yr
Emergy from imported resources, F	4.20E+19	seJ/yr
Total emergy U=R+N+F	4.37E+19	seJ/yr

3.4 Emissions and impact categories

The total contribution of the investigated systems to the impact categories (Carbon Footprint, Human Toxicity, Photochemical Oxidation, Acidification, Eutrophication) as well

as the contribution per unit of product (gram of treated wastewater, gram of dry matter or energy content of willow, energy content of heat and electricity) was calculated by means of the CML2-baseline 2000 method.

Results of the impact assessment for heat and electricity production are summarized in Table 4. A predominant environmental benefit of biomass energy should be the carbon neutrality between CO₂ sink and emissions: the CO₂ emitted by utilizing the bioenergy should be balanced by the CO₂ absorbed in cropping the biomass, thus resulting in no net increase of atmospheric CO₂. Actually, by investigating the entire life cycle of the production chain, most often emerges that this condition is not verified.

The total Carbon Footprint of the CHP plant resulted $8.81 \cdot 10^{10}$ g CO₂ eq. per year. This value accounts for all the emissions due to direct and indirect fossil energy consumption (transportation of biomass to the CHP plant, power plant construction, etc). Moreover, several sources of CO₂ emissions also exist in the wastewater treatment and cropping systems (farming activities, manufacturing, field transport, etc.). In addition, other greenhouse gases such as N₂O and CH₄ also contributed to the global warming potential of the production system.

Table 4. Results of CML 2 – baseline 2000 method for the CHP plant.

Impact Categories (CML 2 - baseline 2000)	Value	Unit
Carbon Footprint	8.81E+10	g CO ₂ eq.
Carbon Footprint of electricity	1.05E-04	g CO ₂ eq./J
Carbon Footprint of heat	2.10E-04	g CO ₂ eq./J
Human Toxicity	2.64E+08	g 1,4-dichlorobenzene eq.
Human Toxicity of electricity	3.15E-07	g 1,4-dichlorobenzene eq./J
Human Toxicity of heat	6.30E-07	g 1,4-dichlorobenzene eq./J
Photochemical Oxidation	7.57E+07	g ethylene eq.
Photochemical Oxidation of electricity	9.02E-08	g ethylene eq./J
Photochemical Oxidation of heat	1.80E-07	g ethylene eq./J
Acidification	1.31E+08	g SO ₂ eq.
Acidification of electricity	1.57E-07	g SO ₂ eq./J
Acidification of heat	3.13E-07	g SO ₂ eq./J
Eutrophication	2.99E+07	g PO ₄ eq.
Eutrophication of electricity	3.57E-08	g PO ₄ eq./J
Eutrophication of heat	7.14E-08	g PO ₄ eq./J

3.5 Scenario analysis

After the application of the SUMMA method to the bioenergy production system, optimization scenarios were implemented by selecting different alternative in terms of transportation distances of wood biomass to the CHP plant.

The three main scenarios were:

- Scenario A (actual transportation distances): residues from forestry = 90 km, residues from wood industries = 200 km, willow biomass 10 km.
- Scenario B: decrease by 50% of the transportation distances of residues from forestry and wood industries.
- Scenario C: decrease by 80% of the transportation distances of residues from forestry and wood industries.

Scenarios B and C assume an increased use of local wood biomass sources by recycling wood residues from local agricultural and industrial activities.

Selected indicators for each method, resulting from the variations according to the 3 Scenarios, are shown in Table 5. All the indicators decreased in both Scenario B and C, highlighting the important role played by the transport in relation to the environmental performance and sustainability of the investigated system. Best figures were obtained in Scenario C. The indicators characterizing the three scenarios are shown within the radar diagram (Figure 1). To be able to compare indicators with different orders of magnitude (Table 5), a normalization procedure was applied (Figure 1). Considering that a wider area means an higher environmental impact, Scenario C resulted the best solution with the smallest impact (Figure 1).

Such an outcome can be explained by considering that the reduction of trucking distances involves not only a lower direct consumption of diesel and less airborne emissions, but also a lower indirect consumption of energy, material, and environmental support.

Table 5. SUMMA indicators for three different scenarios: Scenario A (business as usual); Scenario B (-50% of trucking distances); Scenario C (-80 % of trucking distances).

Indicators	Scenario A	Scenario B	Scenario C
Transformity of electricity (seJ/J)	1.21E+05	1.18E+05	1.15E+05
Transformity of heat (seJ/J)	6.07E+04	5.89E+04	5.77E+04
Environmental Loading Ratio, (ELR)= (F+N)/R	2.20	2.13	2.08
Emergy Yield Ratio, (EYR)=F/(R+N+F)	1.04	1.04	1.04
Emergy Sustainability index , (ESI)= ELR/EYR	0.47	0.49	0.50
Oil equivalent intensity per J of electricity (g_{oil}/J)	6.37E-06	6.17E-06	6.04E-06
Oil equivalent intensity per J of heat (g_{oil}/J)	1.59E-06	1.54E-06	1.51E-06
EROI	9.37	9.45	9.58
Total abiotic material requirement (g/yr)	2.49E+10	2.46E+10	2.44E+10
Total water demand (g/yr)	5.30E+11	5.28E+11	5.27E+11
Carbon footprint ($g_{CO2 eq.}$)	8.81E+10	8.78E+10	8.76E+10
Human Toxicity ($g_{1,4-dichlorobenzene eq.}$)	2.64E+08	2.63E+08	2.62E+08
Photochemical Oxidation ($g_{ethylene eq.}$)	7.57E+07	7.54E+07	7.53E+07
Acidification ($g_{SO2 eq.}$)	1.31E+08	1.30E+08	1.29E+08
Eutrophication ($g_{PO4 eq.}$)	2.99E+07	2.98E+07	2.96E+07

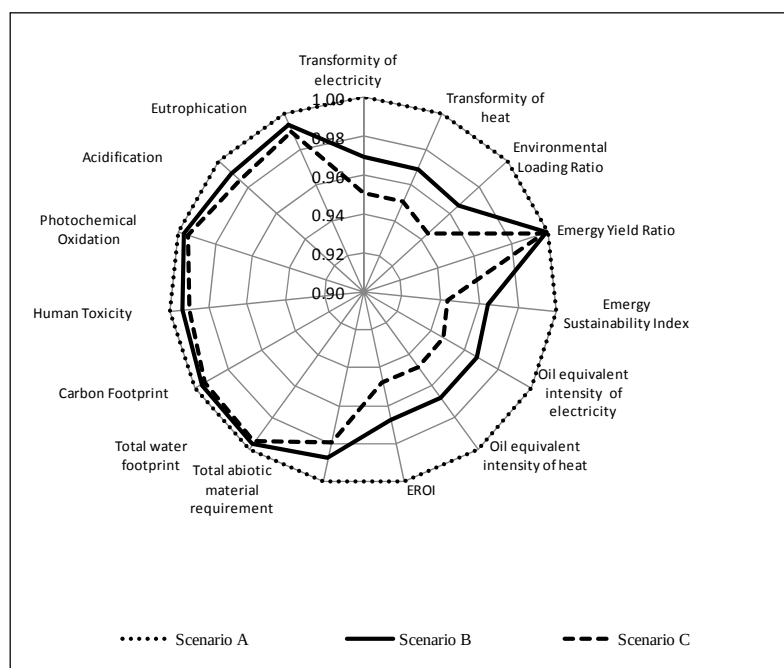


Figure 1. SUMMA indicators for three different scenarios: Scenario A (business as usual); Scenario B (-50% of trucking distances); Scenario C (-80 % of trucking distances). Indicators were normalized from Table 5 by dividing all values by the values of Scenario A.

4. CONCLUSIONS

The results presented in this study provide a comprehensive assessment of the environmental performance and sustainability of the Enköping bioenergy production plant. The use of wastewater for willow irrigation and of wood residues from agricultural and industrial processes reduces the environmental cost for both systems: the willow farming and the CHP plant.

The CHP plant showed an increase of the renewability of electricity generation by using wood biomass, also if fossil fuels were still directly and indirectly required in each step of the integrated production process. An optimization effort to improve the environmental performance and impact of the bioenergy production system could be done through the minimization of biomass transportation distances.

ACKNOWLEDGEMENTS

The Authors gratefully acknowledge the financial support received from the European Commission within the 7th Framework Program, Project no.217213, SMILE - Synergies in Multi-scale Inter-Linkages of Eco-social systems. Socioeconomic Sciences and Humanities (SSH) Collaborative Project FP7-SSH-2007-1.

REFERENCES

- Bargigli, S., Raugei, M., Ulgiati, S., 2005. "Mass flow analysis and mass-based indicators". In: Jorgensen, Sven E., Costanza, Robert, Xu, Fu- Liu (Eds.), *Handbook of Ecological Indicators for Assessment of Ecosystem Health*. CRC Press, pp. 353–378
- Börjesson P., Berndes G., 2006. "The prospects for willow plantations for wastewater treatment in Sweden". *Biomass and Bioenergy*, 30: 428-438.
- Brown, M.T., Ulgiati, S., 2002. "Emergy evaluations and environmental loading of electricity production systems". *Journal of Cleaner Production*, 10 : 321–334.

- Brown, M.T., Ulgiati, S., 2004. "Energy Quality, Emergy, and Transformity: H. T. Odum's contribution to quantifying and understanding systems". *Ecological Modelling*, 178: 201-213.
- Dimitriou, I., Aronsson, P., 2004. "Nitrogen leaching from short-rotation willow coppice after intensive irrigation with wastewater". *Biomass and Bioenergy*, 26: 433-441.
- Franzese P.P., T. Rydberg, G.F. Russo., S. Ulgiati, 2009. "Sustainable biomass production: a comparison between Gross Energy Requirement and Emergy Synthesis methods". *Ecological Indicators*, 9: 959-970.
- Hagström, P., 2006. *Biomass Potential for Heat, Electricity and Vehicle Fuel in Sweden*. Tesi di dottorato, Swedish University of Agricultural Sciences, Uppsala.
- Herendeen, R.A., 1998. "Embodied Energy, embodied everything. . .now what?" In: Ulgiati, S. et al. (Eds.), *Advances in Energy Studies. Energy Flows in Ecology and Economy*. Musis Publisher, Roma, Italy, pp. 13-48.
- Hinterberger, F., Stiller, H., 1998. "Energy and material flows". In: Ulgiati, S. et al. (Eds.), *Advances in Energy Studies. Energy Flows in Ecology and Economy*. Musis Publisher, Roma-Italy, pp. 275-286.
- IFIAS, "International Federation of Institutes for Advanced Study, 1974". In: Slesser, M., (Ed.), *Energy analysis workshop on methodology and conventions*. Report IFIAS No. 89, Stockholm.
- McCormick K., Kaberger T., 2005. "Exploring a pioneering bioenergy system: The case of Enköping in Sweden". *Journal of Cleaner Production*, 13: 1003-1014.
- Odum, H.T., 1988. "Self organization, transformity and information". *Science*, 242: 1132-1139.
- Odum, H.T., 1996. *Environmental Accounting. Emergy and Environmental Decision Making*. John Wiley & Sons, New York, USA.
- Rosenqvist, H., Roos, A., Ling E., Hektor, B., 2000. "Willow growers in Sweden". *Biomass and Bioenergy*, 18: 137-145.
- Schmidt-Bleek, F., 1993. "MIPS re-visited". *Fresenius Environmental Bulletin*, 2: 407-412.
- Ulgiati, S., Bargigli, S., Rauei, M., 2006. "An Emergy of Complexity, Information and Technology, Towards Maximum Power and Zero Emission". *Journal of Cleaner Production*, 15: 1359-1372.
- Volk A. T., Verwijst, T., Tharakan, J.P., Abrahamson L. P., White, E. H., 2004. "Growing fuel: a sustainability assessment of willow biomass crops". *Front Ecol Environ*, 2(8): 411-418.
- Wright, L., 2006. "Worldwide commercial development of bioenergy with a focus on energy crop-based projects". *Biomass and Bioenergy*, 30: 706-714.
- Wuppertal Institute, 2009. "Resource productivity in 7 steps. How to develop eco-innovative products and services and improve their material footprint." *Wuppertal spezial* n. 41.

AN ANALYSIS OF TECHNICAL ALTERNATIVES IN A WASTEWATER TREATMENT PLANT BY USING SLUDGE AS ENERGY RESOURCE

Beatriz Carrasquer , Amaya Martínez and Javier Uche*

CIRCE foundation, University of Zaragoza, Spain

ABSTRACT

Different stages in industrial systems can be disaggregated and analyzed to be optimized, not only improving the economical efficiency of the process, but also to fulfil with the current legal requirements imposed by authorities on the European context. In this way, when an important quantity of residues containing available energy is obtained throughout an industrial process, an interesting opportunity to self feeding energy exists. The available energy can be always measured by an objective and universal unit: the exergy (or valuable energy contained in an energy or matter flow). A comprehensive study of different flows of a wastewater treatment plant was carried out in this work, making possible to calculate the efficiency of the process, as well as the Unit Exergy Cost (k^*) for different equipments. This parameter is defined as the ratio between the valuable energy contained in fuel and products flows, in a given process. Preliminary results shown that, considering different kinds of sludge energy valorization, its anaerobic treatment seems to be a very interesting way to really obtain electrical and thermal own-feeding, by burning the obtained biogas in an internal combustion engine. It makes possible to improve the efficiency of the plant as much as five percent. Additionally, k^* values of the process are diminished, as expected. They varied depending on the quantity of electricity obtained (from zero to twenty-five percent) with respect to the amount of energy required in the whole process.

Keywords: Exergy approach, sludge valorization, waste water treatment

1. INTRODUCTION

Energy, technology and economical investment are main factors to restore or avoid degradation of water bodies. Due to the change in the quality of energy that accompanies flows conversion from one energy form to another, many energy losses occur. For instance, the energy which is contained in residues can be used as a source to provide self-feeding energy.

Regarding legal requirements, different Directives should be taken into account, at the European Context. First of all, waste water discharge, collection, treatment and mixture, are regulated by the European Council Directive 91/271/CEE, aimed to protect the environment in urban and industrial sectors. The monitoring of the performance in wastewater treatment plants (WWTP) as well as controls of sewage sludge disposal and reuse are demanded. Additionally, the Water Framework Directive adopted in 2000, forces all European Member Countries to recover all water bodies to their Objective Status [The European Commission, 2009].

Many authors performed an estimation of the consumption of physical resources for wastewater treatment plants. Contributions such as [Hellström, 1997] or [Lundin et al, 1997] were pioneers in the study of these processes. The former made an

* Corresponding author; E-mail: becarras@unizar.es

estimation of the consumption of physical resources, while the latter accounted for indicators to develop this kind of systems.

During last decade, other contributions such as [Balkema, 2002] or [Muga et al, 2008] continued within this field of research. Nevertheless, one of the most important references, and main basis of this work, is the Exergy Costs methodology, proposed by [Valero et al, 1986a]. It constituted the startup of some other studies such as [Velásquez et al, 2007], [Mora-Bejerano and Oliveira, 2009], [Martínez, 2009], or [Martínez et al, 2010]. Main differences of that methodology from other accounting tools lie in considering an energy conversion between heat and mechanical work.

Different parameters defined in those previously mentioned works can be found in the literature. They are summarized along next section.

2. METHODOLOGY

A natural resource must be changed chemically and physically up to the required conditions depending on the objective of later uses. Therefore, its thermodynamic value, that is, the minimum work necessary to produce it with a specific structure and concentration from common materials in the environment is theoretical and equal to the material's exergy value (B).

In case of water, that thermodynamic property is defined by its mass flow and six parameter measurements that characterize its physical conditions: mass flow, as well as temperature, pressure, height, velocity, concentration and composition. Although each natural resource needs a particular analysis framework, identifying the most relevant features of the resource and obtaining its physical and chemical characterization (which makes it differ from the surroundings), selecting the most suitable reference environment for the resource (for instance, sea water, that is a proper reference for a fresh water resources evaluation) and, finally, calculating the valuable energy of the evaluated resource, are needed for a comprehensive water assessment [Martínez, 2009].

Since exergy analysis is carried out by means of thermodynamic macroscopic variables such as temperature, volume and pressure, it can be considered far above other kinds of process evaluations which are subjected to controversy due to the special interest that they provoke in the society. The exergy analysis of technological processes has been widely used to analyze the performance of industrial systems during last years. It can be usually carried out by calculating and studying the exergy of the appearing flows. Regarding to water treatment plants, the raw dirty water and the chemical components and energy flows are the inputs. Clean water flow and residues are the output flows.

A wide variety of ratios, parameters and indicators have been developed for waste water treatment evaluation in order to analyze the minimization of energy losses.

Since the difference between the exergy of fuels and products determines the energy losses in a system, exergy efficiency (η) was defined in [Valero et al, 1986a] as the proportion of products valuable exergy (P) in relation of input energy in fuel flows (F) (see Eq. (1)).

$$\eta = \frac{P}{F} \quad (1)$$

In this sense, the Unit Exergy Cost (k^*), was defined in [Valero et, 1986a] as the inverse of η , as follows (see Eq.(2)):

$$k^* = \frac{F}{P} \quad (2)$$

The Environmental exergy efficiency ($\eta_{\text{env.exerg}}$) of a process was defined in [Velásquez et al, 2007] and [Mora-Bejerano and Oliveira, 2009] as the ratio between

the exergy of the products and the total exergy consumed in that process, as shown in Eq. (3):

$$\eta_{env.exerg} = B_{products} / B_{totalconsumed} \quad (3)$$

While Eq.(3) is based only in thermodynamics, an influence not only by thermodynamics, but also by economic aspects can be seen in Eq.(1). Then, Thermoeconomics was defined in [Valero et al, 1986b], as a new Science that joins thermodynamics, economy and ecology.

Other parameters related to the assessment of environmental degradation, such as renewability and costs indexes were developed. Firstly, the renewability index was calculated in [Velásquez et al, 2007] and [Mora-Bejerano and Oliveira, 2009] by Eq.(4):

$$\lambda = B_{products} / B_{lost} \quad (4)$$

Where $B_{products}$ is the exergy contained in the useful products, and B_{lost} stands for the exergy which is destroyed and/or remains on emissions and residues.

2.1. Specific exergy accounting applied to a wastewater treatment plant

The available energy contained in water diminishes during its cleaning treatment, since the input water exergy includes not only the value of water as inorganic substance, but also the values of other flows which are eliminated as residues (organic matter, nitrogen and phosphorous, fats, or sand). Then, it was considered interesting to define the efficiency of that processes ($\eta_{elim.res}$) by means of the exergy contained in the residues applying Eq. (5).

$$\eta_{elim.res} = \frac{b_{residues}}{b_{IW} + electricity} \quad (5)$$

Where $b_{residues}$ and b_{IW} are the specific exergies of residues (sludge, fat, sand, combustion gases), and input water (IW), respectively. *Electricity* stands for the input of external power. According to Eq. (5), the higher efficiency of the process, the bigger exergy of residues.

Other exergy-related useful parameter is the unitary exergy cost. Two different unitary exergy cost were defined [Martínez, 2009], by applying Eq. (2): the unitary exergy cost of the process ($k_{process}^*$) and the unitary exergy cost of the product ($k_{product}^*$). In the exergy cost of the process, the whole exergy behavior of the process is considered. All the outputs are taken as products. In the exergy cost of the product, only the desired output is considered and all the inputs are assigned to it.

Additionally, it was very interesting to evaluate a new unitary cost, $k_{elim.res}^*$, defined by Eq. (6):

$$k_{elim.res}^* = \frac{1}{\eta_{elim.res}} \quad (6)$$

It is worth to highlight that $k_{process}^*$ and $k_{elim.res}^*$ can be compared with $k_{product}^*$ by calculating the ratios between them. This accounting was also useful to analyze the $\eta_{env.exerg}$ and previously defined), by applying Eqs. (7) and (8), respectively.

$$\eta_{env.exerg} = \frac{k_{process}^*}{k_{product}^*} \quad (7)$$

$$\lambda = \frac{k_{elim.res}^*}{k_{product}^*} \quad (8)$$

2.2. Exergy flows assessment of a wastewater treatment plant

Empirical equations and thermodynamic approximations were considered to finally obtain the valuable energy content of each internal flow in the water treatment process, first path of this comprehensive study. Some key issues to carry out the exergy flows accounting are summarized here. All of them are schematized in Fig. 1.

- Energy contained in electricity flows is absolutely valorizable. An important percentage of the electricity requirements in Spanish WWTP are currently supplied by the combustion of biogas produced in their processes [EVE, 2001]. Remaining electricity demand is externally supplied. Regarding internal consumptions, the 60 % of the total electricity demand is consumed in the anaerobic digestion [Bradfer, 2005], and the other 40 % is divided between electricity requirements of sand and fat elimination step, aerobic digestion, and stabilization stages [UPV, 2010].

- Air flow enters at environmental conditions. Then, its exergy is equal to zero since temperature and pressure values are equal to reference conditions.

- Exergies of sludge, sand, fat, inorganic substances (including salts and water contribution), and chemical components were calculated attending to their physical features. Process data were taken from [IAA, 2005] and [INE, 2007] and a more detailed procedure can be found in [Martínez et al, 2010].

- Water flows. The addition of water flows, as an inorganic substance, and the remaining sludge in each treatment stage, were also considered in order to calculate the water flow exergy in each WWTP stage.

After the exergy flows accounting was carried out, it was concluded that the sludge is the residue which contains more quantity of valuable energy in a wastewater treatment plant process. Then, when a remaining important quantity of this sludge with the adequate composition is obtained, it is highly recommended to go on its further valorization. There exist different alternatives to perform that valorization [Castells and Cadavid, 2005], as follows:

- Aerobic sludge digestion, in presence of oxygen. Resulting sludge can be used in agriculture as compost. It is directly delivered over the crops soils.

- Sludge thermal treatments, such as combustion, incineration and gasification. Previous dewatering of the sludge, the organic matter is oxidated. Other stages included in this treatment, such as separating particles, eliminating moisture, or cooling, imply a complex and quite expensive system.

- Anaerobic sludge treatment. It consists on introducing the sludge, with approximately four percent of organic matter (OM), in an anaerobic reactor, to obtain biogas. It can be burnt in a combustion engine, generating electricity and preheated water to be used within the WWTP process. The digested dry sludge can be then filtrated and used as fertilizer.

- Finally, it is also possible the reutilization of sludge in certain industries as a commodity, attending to economic aspects, such as transport, and profitability. In case of impossible valorization due to the presence of toxic or metallic substances, sludge has to be treated as a hazardous solid waste, by means of chemical, physical or biological processes.

In this paper, starting from the theory proposed by [Valero et al, 1986a], the contributions summarized in this section were applied for the study of a WWTP sited at the Huerva river, Spain. After analyzing these alternatives, anaerobic sludge treatment was considered the best, and taken into account in the analyzed case study.

3. A WWTP CASE STUDY ANALYSIS

Any kind of waste could be an energy source since contained available energy always implies an opportunity to diminish residues and emissions generation. The analyzed WWTP case study, located in the Huerva river, a tributary of the Ebro Basin

in Spain, does not include any energy valorization of residues in its current running scheme. The possibility of adding an anaerobic sludge treatment (according to the conclusions of section 2) to obtain useful energy was evaluated in detail within this study. Main process stages, including the chemical processes occurred in it, as well as some specific consideration about the exergy flows assessment, complete this section

3.1. Main process stages considering sludge valorization

The stages and flows involved in the real case study, at which a typical sludge anaerobic treatment stage was added are summarized in Fig. 1.

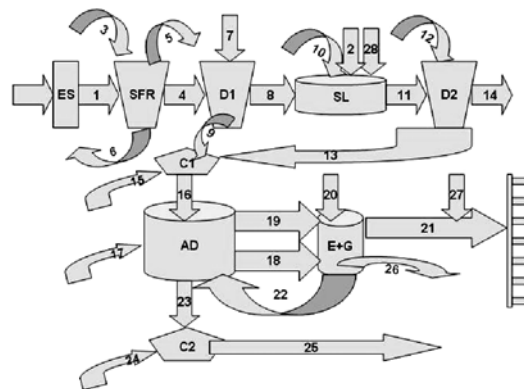


Fig. 1. A WWTP scheme with sludge valorization by anaerobic treatment plus biogas combustion

All the stages and flows are listed here:

STAGES

1. Solids Removal (SR)	6. Primary concentration of sludge –centrifuge 1-(C1)
2. Sand and fat removal (SFR)	7. Anaerobic digestion –anaerobic digester- (AD)
3. Primary decantation -decanter 1- (D1)	8. Combustion + alternating-current generation – engine plus generator- (E+G)
4. Biologic Aerobic treatment –Stabilization lagoons- (SL)	9. Secondary concentration of sludge centrifuge 2- (C2)
5. Secondary decantation –decanter 2- (D2)	

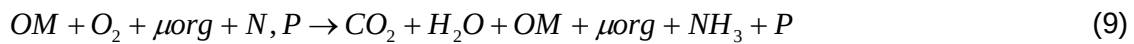
FLOWS

1. Water flow after solids removal	14. Fresh water (WTP output product)
2. Air input (aerobic treatment)	15. Electricity consumption (primary decantation)
3. Electricity consumption (sand and fat elimination)	16. Concentrated Sludge (primary decantation output)
4. Water flow after sand and fat elimination	17. Electricity consumption (anaerobic digestion)
5. Recovered fat	18. Anaerobic reactor output water (closed circuit)
6. Recovered sand	19. Biogas (anaerobic digestion)
7. Electricity consumption (primary decantation)	20. Air at environmental conditions (engine input)
8. Water flow after primary decantation	21. Obtained electricity by biogas combustion
9. Primary decantation of sludge	22. Preheated water (closed circuit)
10. Electricity consumption (aerobic treatment)	23. Digested sludge
11. Aerobic treatment output water	24. Electricity consumption in the secondary concentration
12. Electricity consumption (secondary decantation)	25. Final sludge, dry and digested
13. Secondary decantation of sludge	

3.2. Chemical processes in aerobic and anaerobic water treatments

Some important issues to highlight about the difference between aerobic and anaerobic treatments, carried out in wastewater treatment plants, are included here.

The main active agents in Biologic Aerobic treatment are bacteria and protozoe which oxidate OM and nutrients as Nitrogen (N) and Phosphorus (P) in oxygen presence [Peralta and Barea, 2009]. Oxygen feeding is a way to maintain the desired conditions for the aerobic degradation with a richness of oxygen up to the eighty-five percent. Main products in this stage are carbon dioxide (CO₂), water (H₂O), ammonia (NH₃), P, not reacted OM, and, additionally, new microorganisms (org). This process is schematized in Eq.(9).

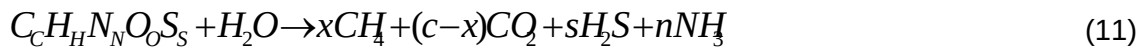


Some kinds of protozoe, as amoebas or ciliades, or bacteria such as cyanobacteria or pseudomone, are main oxidation agents in this step. Conversion for organic matter to biomass (org) is about the 40 percent [Castells and Cadavid, 2005]. Additionally, coagulation and flocculation process are included in this stage of aerobic digestion [Peralta and Barea, 2009]. They start with a stage of electrical instability. Then, the electrical link between opposite-sign molecules makes them to group themselves obtaining bigger items, whose precipitation is easier. One of the chemical components more commonly used in this stage is the iron trichloride.

Regarding Aerobic stabilization stage (see concentration stages) an endogen process (org auto-degradation), in oxygen presence, generates CO₂, water and ammonia (see Eq.(10)). Mineralization of OM implies the volume reduction and the sludge stabilization [Peralta and Barea, 2009].



In the Anaerobic treatment, Mesophila bacteria work at approximately 35°C. Three main steps are included in this process [Bradfer, 2001], [Riau et al, 2007]: the first of these steps is the Hydrolysis, by which big organic molecules are divided in simpler ones such as acids, aminoacids, aldehyde, or cetona. These molecules can be more easily degraded in an Acidogenesis step (pH of 6.8, approximately), in which acetic or lactic acids are generated. The third step is called Methanogenesis (pH of 7.4 approximately). It consists mainly on the degradation of these acids to methane (CH₄), and CO₂. Conversion of organic matter to biomass is a 4% lower than in the aerobic treatment. However, odour and volume are reduced and disinfection rate is higher [Bradfer, 2001]. The general anaerobic process is schematized by Eq.(11).



3.3. Specific exergy flows assessment

In case of sludge anaerobic digestion, some other flows apart from the specified in section 2.2 should be considered. Their accounting methodology is included below.

- Biogas (flow 19). This exergy was calculated as the product between its High Heating Value (HHV), and the generated biogas flow [EVE, 2001].

- Combustion gases exergy (B_g) was calculated according to process data for the WWTP case study found in [IAA, 2005], [INE, 2007] and [EVE, 2001], by applying the basic equations of Thermodynamics to gaseous substances.

- Closed water loop. Water is heated into the engine, during the combustion, assuring the necessary temperature to a proper inorganic mesophilic microorganism activity inside the reactor [Riau et al, 2007]. During the exothermic anaerobic digestion, the temperature rises up. But this increment is not enough to assure the typical operating temperature for this process (35-40 °C). Closed hot-water flow circuit operates between forty (engine output temperature) and 20 °C (anaerobic reactor output temperature). Therefore, the variation of specific exergy between both saturated liquid states was calculated by thermodynamics.

4. RESULTS DISCUSSION

According to Table 1, were exergy values obtained for different flows are shown, it can be considered that raw input water (flow 1) contains approximately 3 kWh/m³ of treated water, from which 2.47 kWh/m³ are contained in the sludge (flow 16).

FLOWS	b (kWh/ m ³ treated water)	FLOWS	b (kWh/ m ³ treated water)	FLOWS	b (kWh/ m ³ treated water)	FLOWS	b (kWh/ m ³ treated water)
1	3.29	8	1.05	15	0.06	23	2.48
2	0.00	9	2.23	16	2.47	24	0.06
3	0.06	10	0.06	17	0.36	25	2.11
4	3.28	11	1.05	19	0.52	26	0.01
5	0.00	12	0.00	20	0.00	27	0.60
6	0.01	13	0.25	21	0.15	21+27	0.75
7	0.00	14	0.80	22-18	0.31	28	0.00

Table 1. Exergy flows

Since the quantity of required electricity in the process (flows 21+27) is close to 0.7 kWh/m³ [EVE 2001], and supposing an energy cost equal to 12 ctEuro/kWh, the ratio between monetary value of waste to be valorized is more than three times the cost of cleaning this input water. Among the different alternatives studied in section 2, the addition of a typical stage in which sludge is anaerobically treated seems to be the most suitable method to recover valuable energy from waste. Electricity is distributed for different plant uses. The anaerobic reaction is the stage by which more electricity is required. Table 2 shows the efficiencies calculated by following Eq. (11), for different equipments. The obtained value for the combustion engine plus power alternator (E+G) is very high compared with a conventional internal combustion stage. However, and according to [EVE, 2001], this kind of process has a conversion to useful energy values which is much higher than conventional ones. It is due to the obtained electricity and hot water. The exergy efficiencies of these processes can reach up to the 75-95 %.

Equipments	$\eta_{elim.res}$	Equipments	$\eta_{elim.res}$
SFR	0.98	C1	0.98
D1	0.95	AD	0.5
SL	0.95	E+G	0.9
D2	0.99	C2	0.97

Table 2. Equipments efficiencies

Global plant efficiency accounting is represented in Fig. 2, for different percentages of electricity self-generation (compared with the total amount required by the system). As it can be seen, the global plant elimination of residues efficiency calculated by applying Eq. (5) is equal to 0.52 in a process without sludge valorization. Considering sludge anaerobic digestion plus biogas combustion, global efficiency rises until 0.55. Electricity generation greatly depends on the global efficiency of the conversion process from biogas to power, which represents a maximum value of 35% [EVE, 2001] in WWTP biogas combustion processes. This is why, for a given plant capacity, this efficiency determines a maximum of generated electricity. In the analyzed WWTP case study, its value is close to the 25 % compared with the power consumption in the whole process.

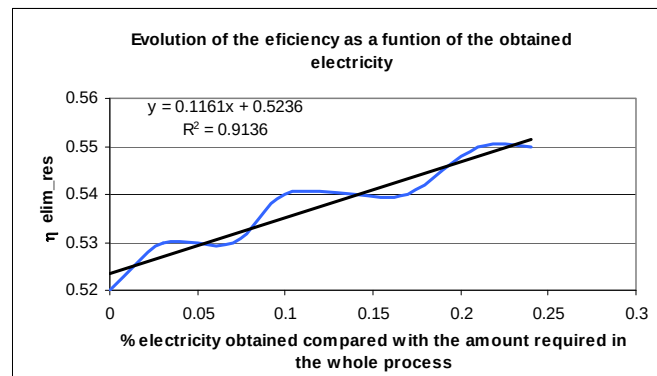


Fig. 2. Evolution of the residues elimination efficiency vs percentage of electricity obtained

Results for different values of $k_{elim.res}^*$, $k_{process}^*$ and $k_{product}^*$ are summarized in Table 3. As expected, k^* increased when the percentage of electricity generated diminishes. Its values were very similar to those obtained in [Martínez, 2009] for twelve real WWTPs. In these studies, the average value obtained for $k_{process}^*$ and $k_{product}^*$ were close to 2 and 4.5, respectively. Additionally, when all outputs are considered as products ($k_{process}^*$), its value is lower than a half compared with that obtained by considering only the fresh water as product ($k_{product}^*$).

% elect.	$k_{elim.res}^*$	$k_{process}^*$	$k_{product}^*$	% elect.	$k_{elim.res}^*$	$k_{process}^*$	$k_{product}^*$
25	1.82	1.33	4.85	10	1.89	1.35	4.95
15	1.85	1.35	4.90	0	1.92	1.38	5.01

Table 3. k^* values as a function of the percentage of electricity obtained

It is also useful to analyze the average ratios between different k^* values. Similar figures were found in [Mora-Bejerano and Oliveira, 2009] for $env.exerg$ parameters. The obtained values for these parameters in the study and the ratios calculated by Eqs. (7,8) were close to 0.3 and 0.4, respectively

5. CONCLUSIONS

A detailed accounting of a WWTP case study, by means of the Exergy assessment, made possible the comprehensive evaluation of different alternatives in order to optimize this process. The valorizable energy content of different flows was analyzed by means of thermodynamic macroscopic variables such as temperature, volume and pressure.

It was seen that, in WWTPs, the anaerobic treatment of sludge constitutes a viable alternative to sludge valorization, with a diminution in odour and volume, apart from a higher disinfection rate. Very high efficiencies couldn't be expected in this kind of processes, in which liquid dilution and chemical reactions occurs, since its behaviour includes unavoidable losses. However, a reasonable energy benefit from residues is observed. Values obtained for k^* , the unitary exergy cost defined by authors in previous works, resulted to be similar to the ones obtained here. The external energy consumption diminishes when the percentage of electricity produced by the residues rises. It implies an increase in the global plant efficiency, a diminution of operating costs, and a reduction of primary energy consumption. It can be concluded that the disaggregation of industrial process flows, and its assessment by the 2nd Law of thermodynamic based methodology that accounts for energy losses in processes but also valorizing the energy in waste, constitutes the main contribution of this work. It is a key point to avoid energy losses, by proposing alternatives with the objective of improving industrial processes and fulfilling with a more and more restrictive legal requirements to preserve and restore our weak environment.

Nomenclature		Greek symbols	Subscripts
B: Exergy (kJ)	P: Product	: Efficiency	Elim.res.: elimination of residues
F: Fuel	WWTP: Wastewater Treatment Plant	: Renewability index	Env.exerg: Environmental exergy
k^* : Unitary exergy cost		org: Microorganism	

ACKNOWLEDGMENTS

The authors greatly acknowledge the financial support given to this paper, which is under the framework of the IDERE R+D+I project (ENE2007-067191), financed by the Spanish Ministry of Education and Science.

REFERENCES

- Balkema, A.J., Preising, H.A., Otterpohl, R., Lambert, F.J.D., 2002, "Indicators for the Sustainability Assessment of Wastewater Treatment Systems", *Urban water*, Vol. 4., Nº 2, pp 153-161.
- Bradfer, J.F., 2005, *Anaerobic digestión and biogas production: a renewable resource*, Technical Report. Water and Environment congress. AS and D Consulting, Jaén, Spain.
- Castells, E. and Cadavid, X., 2005, *Tratamiento y valorización energética de residuos*, Fundación Universitaria Iberoamericana, Ediciones Díaz de Santos [In Spanish]
- Ente Vasco de la Energía (EVE), 2001, *Energías renovables. Plantas de generación de biogás en vertederos*, [Technical report], Tecnologías avanzadas de generación eléctrica, EVE, Ente Vasco de la Energía. Gobierno Vasco [In Spanish].
- Hellström, D., 1997, "An Exergy Analysis for a Wastewater Treatment Plant: an estimation of the consumption of physical resources", *Water Environmental Research*, Vol.69, pp44-51.
- Instituto Aragonés del Agua (IAA), 2005, *Medio Ambiente Aragón 2004-2005*, IAA, [online report], URL.
- Instituto Nacional de Estadística (INE), 2007, *Informe INE, datos 2007*, Technical Report, INE, Madrid, Spain [in Spanish].
- Lundin, M., Molander, S., Morrinson, G.M., 1997, "Indicators for the Development of Sustainable Water and Wastewater Systems", *Proceedings of Sustainable Development Research Conference 1997, Manchester, United Kingdom*, pp. 1-6.
- Martínez, A., 2009, *Exergy costs assessment of water bodies: Physical Hydraulics*, Ph.D Dissertation, University of Zaragoza, Aragón, Spain
- Martínez, A.; Uche, J.; Rubio, C. and Carrasquer, B, 2010, "Exergy cost of water supply and water treatment technologies". *Desalination and Water Treatment*. Volume 6902.

- Mora-Bejerano, C.H and Oliveira Jr, S., 2009, "Exergoenvironmental evaluation of wastewater treatment processes", *Proceedings of the 22nd International ECOS Conference, August 31-September 3, 2009, Fox do Iguaçu, Brazil*.
- Muga, H. E., Mihelcic, J.R., 2008, "Sustainability of Wastewater Treatment Technologies", *Journal of Environmental Management*, Vol.88, pp 437-447.
- Peralta, J. and Barea, L.M; 2009, *Digestión aerobia: diseño de procesos en ingeniería ambiental*, IMAES, Grupo de Ingeniería Ambiental. E.T.S de ingenieros Industriales, Ciudad real [In Spanish].
- Riau, V.; De la Rubia, M.A; Forster, T.; Pérez, M., 2007, "A comparison between mesophilic and thermofilic sewage sludge digestion. Communication". *II Congreso Internacional Smallwat -International Conference- Cádiz University, Spain*.
- The European Commission, 2009, *Report from the Commission to the European Parliament and the Council in accordance with article 18.3 of the Water Framework Directive 2000/60/CE on programmes for monitoring water status*, Technical report, [SEC(2009)415], Commission of the European Communities, Brussels.
- The European Council, 1991, *Council Directive 91/271/CEE concerning Urban Waste Water discharge, collection, treatment and mixture*, European Union.
- Universidad Politécnica de Valencia (UPV), 2010, *Consumo energético de los tratamientos de agua. Instituto de Seguridad Industrial, Radiofísica y Ambiental. Optimización energética en los usos del agua*. ITA formación. Valencia. Spain. [In spanish]
- Valero, A.; Lozano, M. and Muñoz, M.A, 1986, *A general theory of exergy saving I. On the exergy costs*, Department of Thermoeconomics and Physical Chemistry, Escuela Técnica Superior de Ingenieros Industriales. Universidad Zaragoza. Zaragoza. Spain.
- Valero, A.; Lozano, M. and Muñoz, M.A, 1986, *A general theory of exergy saving I. On the Thermoeconomics costs*, Department of Thermoeconomics and Physical Chemistry, Escuela Técnica Superior de Ingenieros Industriales. Universidad Zaragoza. Zaragoza. Spain.
- Velásquez, H.I., Benjumea, P., Oliveira Jr, S., 2007, "Exergy and Environmental Analysis of the Palm Oil Biodiesel Production Process", *Proceedings of ECOS 2007*, Vol. 1, Padova, Italy, pp.777-784.

LOW CARBON TRANSITION OPTIONS FOR AUSTRALIA

Barney Foran*

*Institute of Land Water and Society, Charles Sturt University
Albury, NSW, Australia*

ABSTRACT

A rapid and sustained transition to new energy systems, either fully renewable (the renewables transition) or through advanced fossil and nuclear technologies (the conventional wisdom transition), can reduce accumulated CO₂ emissions from the Australian economy by 50% out to 2051. Adding a low growth economy where GDP averages less than 1% annually extends this to a 60% reduction. Extensive reforestation of more than 50 million hectares extends the total reduction to 70% over the 45 year period and provides at 2051 a per capita emissions level of one to two tonnes which will be necessary if developed and developing countries are to converge on equal atmospheric impacts with reasonable lifestyle opportunities. Central to both the renewables and conventional-wisdom scenarios are substantial reductions in the physical dimensions of personal consumption, and the transfer of these avoided consumption opportunities to an intergenerational sovereign wealth fund. This fund, held outside day-to-day domestic activities, can buffer Australian society and future generations against shocks, financial or physical, that might lie waiting and unanticipated in our future. This study did not explore phasing out Australia's extensive coal and natural gas exports although their impact on global atmospheric concentrations is significant. Domestic combustion and exported fuels will add 82 billion tonnes of CO₂ to the atmosphere in the scenario period 2006-2051, equivalent to a 20 ppm rise in atmospheric concentrations. The low-growth renewables transition with unconstrained exports reduces this rise to 15 ppm. The continued expansion of fuel exports thus expands atmospheric risk in physical terms but also entrains policy and strategic risks should carbon-based industries become pariahs in international commerce and political relations.

1. THE CONTEXT

Australia, like most developed economies, finds it difficult to practically embrace the transition to a low carbon economy. Its rich endowment of coal and natural gas ensures domestic energy security and buoyant exports for its mining sectors. The political tensions arising from muted outcomes from Copenhagen climate change meetings and proposed legislation for domestic carbon pricing, caused the replacement of both government and opposition leaders by politicians keen to defer carbon mitigation to ensure electoral support, maintain economic growth and employment creation. Yet behind the scenes, globally focused business leaders advocate carbon pricing, the public majority want real action on climate change and the energy system is on the cusp of major investments in renewable energy generation and transmission networks. The issue of peak oil is seldom acknowledged politically although transport fuels are now 70% dependent on imports, adding \$A20 billion to the protracted trade imbalance.

This year saw the release of three major reports advocating a rapid transition to a low carbon economy. The *Low Carbon Growth Plan for Australia* (ClimateWorks, 2010) used the marginal cost curve approach to advocate a 25% reduction in emissions by 2020 at a cost of \$A185 per household per year. The *Australian Sustainable Energy-by the numbers* report (Seligman, 2010) reworked the *Sustainable Energy-without the hot air* approach (Mackay, 2008) to document the engineering and financial feasibility of

* E-mail: Barney.Foran@gmail.com

generation and storage technologies. The *Zero Carbon Australia Stationary Energy Plan* (Wright and Hearps, 2010) analysed a rapid transition over ten years to a 100% renewable electricity infrastructure based on 50,000 MW each of solar concentrating and wind generators at a total project cost of \$370 billion, or less than 4% of GDP annually. The focused renewable energy transitions in these reports were preceded in the previous decade by many reports, most notably the *Garnaut Climate Change Review* (Garnaut, 2008) which used econometric modelling to adjust business-as-usual trajectories by least cost options for lower carbon technologies i.e. the need for radical change was seldom countenanced in serious policy orientated analyses.

This author's *Powerful Choices* report (Foran, 2009) overlapped most of these analyses but focused on the capacity of individual energy technologies to shift emissions trajectories while maintaining economic growth and lifestyle indicators. Meeting the peak oil issue was explored through fossil carbon options (natural gas and shale oil) and plant based options (bio-methanol and bio-ethanol). Similarly, electricity generation options were explored by improvements to the 'conventional wisdom' (advanced coal, combined cycle gas turbines, fuel cells, carbon sequestration and storage, nuclear) or the 'renewables transition' (photovoltaic, solarthermal, wind, biomass). These were left as stand alone analyses because many public policy inquiries and project proposals maintain a case by case evaluation.

This paper brings these technology options together through two coherent world views, currently battling for policy supremacy. The first was the 'renewables transition' driven by the need to transition away from the finiteness of fossil energy supplies and their downstream environmental consequences. The second 'conventional wisdom' worldview relies on the energy density of fossil and nuclear fuels to catalyse the transition to a low carbon economy driven by efficiency of conversion and safe long term storage of residual wastes.

Central to this analysis are four dominant themes from the *Advances in Energy Studies* series. The first is the reliance of economic growth and social commerce on energy transactions first presented by Reiner Kümmel (Kümmel et al. 2002) and later expanded by Robert Ayers, Benjamin Warr and others (Ayers and Warr, 2009). The second is the systemic and life cycle analysis view whether at a whole economy or individual technology/sector level. The third is the rebound effect (Herring and Sorrell, 2009; Madlener and Alcott, 2009) where efficiency improvements drive perverse outcomes of increasing resource use rather than conserving it. The fourth is the importance of solving the peak oil issue or facing civilisation's disruption, if we do not (Hall et al., 2003).

2. METHODS AND APPROACH

The Australian economy is represented as a biophysical-economics model programmed within a systems dynamic framework. The OzECCO model structure (Foran and Crane, 1998) and its application to biofuel production (Foran and Crane, 2000) has been presented at previous conferences. It is described in the *Powerful Choices* report (Foran, 2009), and has been applied to many economies including The Netherlands (Battjes, 1998), UK (Slesser et al., 1997) and the EU (Bockermann et al., 2005). The embodied energy requirement to produce a good or a service is the core analytical concept which allows financial and physical accounts to be maintained in parallel. The structure of the economy is derived from national accounts of capital stocks, input-output tables, financial balance of payments and physical 'stock and flow' accounts of energy, water, land etc. Within OzECCO, each energy technology is described in physical terms from life cycle analyses with productivity quotients capped by thermodynamic and mass balance realities. The model is calibrated over a 24 year historical period 1981-2005 allowing a 45 year scenario period from 2006-2051.

Table 1. Short description of key elements of the ‘renewable energy’ and ‘conventional wisdom’ transitions to a low carbon economy.

Philosophy	Core Scenario Elements	Additional Scenario Dimensions
Renewable Energy Transition	Low carbon electricity generated in equal proportions by photovoltaics, solar thermal, wind and biomass	80% renewable electricity from four generation types, and 90% of transport fuels from thermochemical conversion of wood. Vehicle engines to halve fuel use by 2031
	Methanol replaces petrol and di-methyl-ether replaces diesel by 2030	Add to above, renewable electricity target increased to 95%
	50 m hectares of wood crops grown on cleared agricultural land by 2051 for transport fuel and biomass electricity	Add to above, constrain economic growth to an average of less than 1% for scenario period
	Engine efficiencies double by 2031	Add to above, increase forestry planting by 10 million ha to 60 m ha by 2051
	All other whole-economy assumptions in the base case remain	
Conventional Wisdom Transition	92% of low carbon electricity generated by 23% each from nuclear, advanced coal, combined cycle gas turbines and fuel cells. 80% of fossil plant has CCS operating with a 95% capture. Remainder from hydro and minor wind and biomass	92% conventional wisdom electricity and all natural gas vehicles by 2030
		Add to above, limits to natural gas exports to extend gas cover for domestic economy
		Add to above, vehicle engine efficiencies improve by 50% by 2030
	Natural gas vehicles replace all petrol/diesel vehicles by 2031	Add to above, average GDP growth constrained to less than 1% for scenario duration
	All other whole-economy assumptions in the base case remain	Add to above, increase forestry plantings to 50 m ha by 2051 for forest sequestration of carbon

The ‘renewables’ and ‘conventional wisdom’ scenarios were developed employing the technological production recipe appropriate for that world view (Table 1). By progressively augmenting each core scenario, management nuances were introduced to reduce carbon dioxide emissions while maintaining whole economy objectives such economic growth rates. Generally the data presented here are summed over the scenario period to give a ‘stock’ of accumulated GDP or accumulated CO₂ emissions. This allows a simpler assessment of results where different routes or trajectories to the same outcome are rendered less important. A limited set of ‘stock’ variables or headline indicators are used for reporting (see Tables 2 and 4), although there are many hundreds of relevant indicators available.

Several computational improvements have developed to deal with the rebound effect which often emerges after innovations or shocks. A modelling protocol managed buoyant simulation runs to be GDP-neutral i.e. to meet the GDP outcome of the base case or business-as-usual case. Higher than normal financial flows (caused by technologies or efficiency improvements etc.) were transferred to a sovereign wealth fund held outside the domestic economy and thus unavailable for re-investment and additional consumption, capping economic growth, additional energy use and emissions. Traditionally, central banks mostly use interest rates to manage excess buoyancy but sovereign wealth funds exist for many petroleum exporting countries such as Norway, East Timor and the Middle East. This is an analytical mechanism to rescale results of energy transitions to a common anchor of ‘the same GDP outcome’.

3. RESULTS

3.1 The Renewables Transition

The core renewables scenario of 80% renewable electricity and 90% wood-based biofuel, successfully maintains volumetric GDP in aggregate while reducing accumulated CO₂ emissions by 11.6 billion tonnes or 40% below the base case level (Table 2). Capital stocks of infrastructure are 33% higher than the base case and the wealth fund accumulates to twelve times current annual GDP by 2051. The personal consumption indicator reduces by 24% to make this feasible, but the per capita emission of 21 tonnes by 2051 is substantially higher than the five tonnes threshold required by most atmospheric stabilisation simulations.

Table 2. Core economy-wide indicators for the 'renewable electricity + methanol from wood' scenario, and its scenario derivatives (scenario period 2006-2051; figures in brackets indicate percentage difference from the base case value)

	Base Case	80% RenElect + 50% vehicle efficiency	95% RenElect + 50% vehicle efficiency	+ low GDP growth	+ 60m ha forestry
GDP growth rate %	2.2	2.7	2.3	0.6	0.6
Accumulated GDP \$bn	73,747	73,729	63,491	46,187	46,257
			(-14%)	(-37%)	(-37%)
Accumulated CO ₂ emissions bn tonne	28.7	17.1	14.3	10.3	9.6
		(-40%)	(-50%)	(-64%)	(-67%)
Embodied energy in consumption GJ/capita	7,238	5,517	4,490	3,118	3,116
		(-24%)	(-38%)	(-57%)	(-57%)
Infrastructure capital stocks: embodied PJ	24,672	32,869	27,311	15,620	15,136
		(+33%)	(+11%)	(-37%)	(-39%)
Sovereign wealth fund \$bn	0	12,278	12,409	13,403	13,403
Per capita CO ₂ emissions at 2051	34.9	21.1	15.5	2.9	1.2
		(-40%)	(-56%)	(-92%)	(-97%)

Note: RenElect = renewable electricity with equal proportions of photovoltaics, solar thermal, wind and biomass; the 'methanol from wood' component replaces 90% of petroleum fuel with the thermochemical conversion of wood to methanol and di-methy-ether by 2030.

Increasing the renewable electricity target to 95% decreases volumetric GDP by 14% and the personal consumption indicator by 38% compared to the base case. The infrastructure stocks are still 11% higher than the base case, the wealth fund is maintained while an extra three billion tonnes of CO₂ emissions are avoided giving an overall 50% reduction in emissions over the scenario period. At 2051, the per capita emissions are 15.5 tonnes, a level still not acceptable for a global strategy for atmospheric stabilization.

Two low growth scenarios reduce volumetric GDP by 37% but also reduce accumulated emissions by around 65% compared to the base case. To achieve this, the personal consumption indicator reduces by nearly 60% and the infrastructure stocks by nearly 40%. The wealth fund is 8% higher while the per capita emissions of one to three tonnes are 95% below the base case and agree better with requirements for atmospheric stabilization.

Table 3. Carbon dioxide accounting for the 'renewable electricity + methanol-from-wood' scenario, and its scenario derivatives (all emissions in billion tonnes CO₂, accumulated over the period 2006-2051).

		Base Case	80% RenElect + 50% vehicle efficiency	95% RenElect + 50% vehicle efficiency	+ low GDP + growth	+ 60m ha forestry
Combustion CO ₂		29.807	21.747	19.032	15.118	15.137
Fugitive CO ₂ emissions		0.452	0.556	0.485	0.442	0.442
Forest CO ₂ sequestration		1.558	5.226	5.226	5.226	5.967
Net CO ₂ emissions		28.701	17.077	14.292	10.334	9.612
Biochar CO ₂ at 20% processing residue	0		2.201	1.802	1.229	1.231

Note: RenElect = renewable electricity with equal proportions of photovoltaics, solar thermal, wind and biomass; the 'methanol from wood' component replaces 90% of petroleum fuels with thermochemical conversion of wood to methanol and di-methy-ether by 2030.

The emissions accounting shows three physical realities of the low carbon transition (Table 3). The technology-alone scenario of low carbon electricity and fuels avoids nearly eleven billion tonnes of emissions. Thus a technology solution is capped at around a 30% reduction over the full transition period. The dynamics of forest growth, harvest, combustion and emissions release is important and a stable banking of five to six billion tonnes is maintained throughout all scenarios, giving a standalone component of nearly 20% if maintained. A further four billion tonnes is avoided if economic growth is constrained. Thus only the combination of technology, limited economic growth and large ongoing reforestation will reduce per capita emissions to be compliant with atmospheric stabilisation targets.

However there are important caveats within the renewables scenario. Natural gas retains important functions particularly in high temperature heat for industry such as minerals smelting and cement manufacture. Electricity can replace gas for example in electric arc furnaces for steel smelting. Changing this assumption (i.e. replacing gas for industry with electricity) could avoid an additional three to four billion tonnes over the scenario period. Storage of biochar in agricultural soils could remove a further one to two billion tonnes of CO₂ emissions. Currently, the accounting of the methanol-from-wood process vents carbon not stored in the useable fuel. Due to partial gasification of wood, 20% of wood carbon remains as biochar residue offering a lockup potential for process emissions. Substituting gas with electricity and using biochar for carbon storage could improve the renewables scenarios.

3.2 The Conventional-Wisdom Transition

A rapid transition to advanced fossil generators fitted with CCS, nuclear power and natural gas fuelled vehicles maintains volumetric GDP while avoiding or storing 10-12 billion tonnes of CO₂, a 40% reduction compared to the base case (Table 4). The personal consumption indicator is reduced by around 10% while infrastructure stocks are reduced by a maximum of 10% in the core scenario. The wealth fund at 2051 is three to four times current GDP, but per capita emissions of 16-18 tonnes are not compliant with global atmospheric stabilisation.

Table 4. Core economy-wide indicators for the 'best conventional electricity + natural gas vehicles' scenario and its scenario derivatives (scenario period 2006-2051)

	Base Case	BCE NGV	+ + limit gas export	+ 50% vehicle efficiency	+ low GDP growth	+ 50m ha forestry
GDP growth rate %	2.2	1.8	2.1	2.2	0.8	0.8
Accumulated GDP \$bn	73,747	73,716	73,742	73,774	50,207 (-32%)	50,430 (-32%)
Accumulated CO ₂ emissions bn tonne	28.7	18.2 (-37%)	18.4 (-36%)	16.5 (-43%)	11.6 (-60%)	8.3 (-71%)
Embodied energy in consumption GJ/capita	7,238	6,410 (-11%)	6,622 (-9%)	6,658 (-8%)	4,196 (-42%)	4,165 (-42%)
Infrastructure capital stocks embodied PJ	24,672	22,148 (-10%)	24,283 (-2%)	26,045 (+5%)	15,103 (-39%)	14,918 (-40%)
Sovereign wealth fund at 2051 \$bn	0	3,675	4,024	2,668	6,410	6,410
Per capita CO ₂ emissions at 2051 t/cap	34.9	16.5	18.4	16.5	8.1	2.1

Note: BCE = best conventional electricity (nuclear+advanced coal+ combined cycle gas + fuel cells); NGV = 80% of all vehicle types fuelled by compressed natural gas by 2030.

Reducing economic growth to an average of 0.8% over the scenario period reduces emissions by 60% or 19 billion tonnes, or 70% and 20 billion tonnes if 50 million ha of forestry is established by 2051. A low growth economy reduces volumetric GDP by 32%, the personal consumption indicator by 42% and infrastructure stocks by 40%. The wealth fund accumulates to six times today's GDP and the per capita emissions are reduced to eight tonnes at 2051, or two tonnes with the large forestry expansion.

Table 5. Carbon dioxide accounting for the 'best conventional electricity + natural gas vehicles' scenario and its scenario derivatives (all emission in billion tonnes).

	Base Case	BCE NGV	+ + limit gas export	+ 50% vehicle efficiency	+ low GDP growth	+ 50m ha forestry
Combustion CO ₂	29.807	24.982	25.153	23.047	16.011	16.064
Fugitive Emissions CO ₂	0.452	0.447	0.450	0.461	0.343	0.339
Carbon Capture and Storage	0	5.634	5.664	5.447	3.226	3.206
Forest Sequestration CO ₂	1.558	1.558	1.558	1.558	1.558	4.913
Net Emissions CO ₂	28.701	18.237	18.381	16.472	11.571	8.283

Note: BCE = best conventional electricity (nuclear+advanced coal+ combined cycle gas + fuel cells); NGV = 80% of all vehicle types fuelled by compressed natural gas by 2030.

The high efficiency fossil generators plus nuclear plant avoid between four and six billion tonnes of emissions in the normal growth scenarios (Table 5). The carbon capture

technology stores around 5.5 billion tonnes of CO₂, giving a capping of emissions of around 18 billion tonnes or 16.5 billion tonnes when limits to gas exports and vehicle efficiencies are combined. A lower growth economy reduces the emissions reduction task by up to nine billion tonnes, thus lowering to three billion tonnes the storage task. Adding the 50 million hectare forest estate adds three billion tonnes to biological carbon storage, summing to an overall 70% reduction from the base case in the most extreme scenario of 'low growth plus high forestry'.

3.3 Opportunities and Risks Posed by Each Transition Type

While the core renewable electricity technologies are now mature, the rate of expansion from a low base could be problematical in organisational and skill terms. Over the 45 year scenario electricity infrastructure expands at 25% yearly from a low base currently while the methanol fuel system expands at 13%. A WWF transitions report found that expansion rates of 30% were feasible, that parallel roll out of technologies outperform a sequential least-cost approach, but that a shortage of 28,000 engineering professionals with training lead-times of ten years could be an issue without focused training policies (Mallon and Hughes, 2008). Distributed energy systems at this scale give advantages, unquantified here, such as refurbishment of Australia's industrial base and increased regional economic enterprise.

The advanced fossil and nuclear generators required for the conventional-wisdom approach are also off the shelf. However rolling out the carbon capture and storage system at the scale and performance modelled here is still prospective. While doubt remain about the physical feasibility of injection systems and storage longevity (Ehlig-Economides and Economides, 2010), a recent Australian government task force found that the large continental land mass is capable of 300 million tonnes emissions injection into saline aquifers per year with several hundred years storage certainty, and a total storage potential of 417 billion tonnes CO₂ (Carbon Storage Taskforce, 2009). Thus the six billion tonnes storage requirement here seems feasible, at least to 2051. The report notes the requirement for 3,000 km of CO₂ transporting large diameter pipeline or roughly three times the current inventory. This modelling simulates a four times expansion in the pipeline sector by 2051 and thus replicates the taskforce report.

4. DISCUSSION

4.1 Results in Conflict

The rapid transition to a low carbon economy, whether using renewable or conventional-wisdom approaches, is shown here to be physically feasible. However it is not financially neutral to the economic mainstream and the consumer, if developed-country targets of less than 5 tonnes per capita ensuring atmospheric stabilisation are to be met by 2051. Major studies such as the *Stern Review* internationally and the *Garnaut Review* in Australia use mostly econometric modelling to opine that low carbon transitions can progress with little effects on GDP and a consumer's personal utility. Thus the divide between biophysical economics and conventional economics widens, but a cautionary approach suggests that the modelling approach used here and its underpinning methodologies be first critiqued.

The embodiment or life-cycle paradigm, central to most energy, water and greenhouse policy analyses, is now sufficiently mainstream to minimise challenge. Transposing embodiment into a dynamic modelling platform, now termed stocks and flows modelling, is again mainstream in ecology and science, but not fully embraced by national policy analyses. The modelled sectors here are parameterised by national statistical databases and give headline and sectoral results that accord with traditional analytical platforms and policy agendas. Perhaps the most alternative issue here is the capping and redirection of personal consumption options into a wealth fund to constrain rebound.

However this mechanism functions in real world economies today specifically to control 'Dutch Disease' in resource-rich countries.

There are many technical specifications open to challenge such as the industry sector's requirement for natural gas noted in the renewables scenario. Learning curves (capital cost decreases with technology breakthroughs) have not been used for renewable technologies on the basis that implementation costs will increase once the best and closest sites are taken, and that energy storage will be required as renewable penetration climbs past 40%. However sensitivity analyses show that all core scenarios are robust in the face of variations such as a doubling of capital cost and a 20% reduction in energy yield specifications.

4.2 A Low-Growth Economy

The finding that a low-growth economy is a required component of a low carbon economy is perhaps the most contentious finding here. Yet a reduced consumption indicator (here energy embodied in personal consumption) can be re-interpreted that consumption units become more valued per unit, under conditions of scarcity. None of this discourse is new to biophysical economics where a recent reappraisal of its founding father Nicholas Georgescu-Roegen (Levallois, 2010) and a resurgent end-of-growth scholarship (Lawn and Clarke, 2010) remind us that atmospheric sinks and ecosystem services are approaching limits. Also key energy-dense fuels such as traditional oil may soon be constrained causing inescapable knock-on effects to anticipated growth trajectories. For the most radical scenarios, summing the wealth fund and GDP over 45 years gives a 20% reduction in national monetary terms and a 60% reduction in the physical dimensions of lifestyle consumption. This may be the price of a low carbon economy and converging towards per capita equity in global impacts

4.3 Managing the Rebound Effect

Both transitions explored here stimulate large rebound effects that the wealth fund mechanism constrains. In the renewables case, this is caused by increases in industrial output required to replace the fossil fuelled infrastructure with a much larger array of energy concentrators that are less efficient in traditional terms. By the mid 2030s the new energy infrastructure is in place and rebound is driven by an absence of fuel supply chains and avoiding oil imports.

For the conventional-wisdom case, rebound is due to a doubling of production efficiencies with gas turbines and fuel cells, sufficient in this case to outpace the economic drag from CCS implementation and the higher cost nuclear cycle. Transitioning vehicles from oil to natural gas and reducing gas exports to maintain domestic fuel cover further stimulates rebound compared to the base case. The intricate economy-wide and century-long dissection of the US and other economies by Robert Ayers and colleagues have emphasised the need for step changes in all areas of exergy transformation and work, if economic growth rates are to be maintained. Having explained past rebound realities, that work has not dealt with future rebound control in developed economies. Realistically, many factors such as population ageing, infrastructure failure, extreme events and law and order issues may be sufficient to soak up future rebounds. The rebound control simulated here might be viewed as a possibility rather than a certainty where the wealth fund sizes and shapes the nature of a future policy issue, signalling the advance need for institutions ready to manage the issue.

4.4 Domestic and Exported CO₂ Emissions from the Australian Economy

Transitioning Australia's fossil fuel rich economy to a low carbon functioning ignores the global effect of coal and gas exports and their contribution to radiative forcing and global climate disruption. With domestic combustion and exported fuels, the base-case

Australian economy by 2051 will contribute 82 billion tonnes of CO₂ to the biosphere (29 bt domestically, 53 bt exported). Assuming that half of this is absorbed by oceans and land leaves an atmospheric residual of 41 billion tonnes which equates to a 20 ppm rise in atmospheric CO₂ concentrations. Accounting methods may eventually allocate these emissions to countries where combustion occurs but the coexistence of radical domestic mitigation activities alongside export industries which swamp those efforts globally, provokes an uncomfortable moral tension. With emissions exports maintained, the low growth renewables scenario restricts the atmospheric effect to a 15 ppm rise, a 5 ppm decrease.

4.5 Political Realities

The three core messages here of a large rapid energy transition, a low-growth economy and at least a halving of physical consumption levels are unlikely to attract today's policy advisor. Self interest by consumer-voters and industries make for an intractable political setting for two of the issues, the low-growth economy and reduced personal consumption. Perhaps the energy transition will refurbish the industrial base (long lost to China and low wage countries) and provide a wide range of skilled employment opportunities (ACF 2010). Seemingly the transition dialogue is moving at a glacial pace but behind the scenes there are well entrenched renewable energy targets, a large stock of institutional investment funds awaiting formalised carbon prices, paralleled by academic and media discussion of a carbon tax linked to an intergenerational sovereign wealth fund. Possibly, the transition has already begun.

REFERENCES

- ACF (2010). *Creating Jobs – Cutting Pollution: The roadmap for a cleaner, stronger economy. Report* prepared by NIER for the Australian Conservation Foundation and the Australian Council of Trade Unions, 15th May 2010, 40pp. http://www.acfonline.org.au/uploads/res/ACF_Jobs_report_190510.pdf accessed 15-9-2010
- Ayres, R.U. and Warr, B (2009). *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar, Cheltenham UK 411pp.
- Battjes J.J. (1999). *Dynamic Modelling of Energy Stocks and Flows in the Economy: An Energy Accounting Approach*. PhD Thesis, University of Groningen, 215pp. <http://dissertations.ub.rug.nl/FILES/faculties/science/1999/j.j.battjes/thesis.pdf> accessed 10-9-2010
- Bockermann A., Meyer B., Omann I. and Spangenberg J.H. (2005). "Modelling sustainability: Comparing an econometric (PANTA RHEI) and a systems dynamic model (SuE)". *Journal of Policy Modelling* 27,189-210.
- ClimateWorks Australia (2010). *Low Carbon Growth Plan for Australia*. March 2010, 155pp. <http://www.climateworksaustralia.com/Low%20Carbon%20Growth%20Plan.pdf> accessed 7-9-2010
- Carbon Storage Taskforce (2009). *National Carbon Mapping and Infrastructure Plan – Australia: Concise Report*. Department of Resources, Energy and Tourism, Canberra, 78 pp. September 2009. <http://www.ret.gov.au/resources/Documents/Programs/CS%20Taskforce.pdf> accessed 13-9-2010
- Ehlig-Economides C. and Economides M. (2010). "Sequestering carbon dioxide in a closed underground volume". *Journal of Petroleum Science and Engineering* 70,123-130.
- Foran B. and Crane D. (1998). "The OzECCO embodied energy model of Australia's physical economy". pp.579-596 in *Advances in Energy Studies: Energy Flows in Ecology and Economy*, Porto Venere, May 26-30 1998.
- Foran B. and Crane D. (2000). "Modelling the transition to a biofuel economy in Australia". pp.423-439 in *Advances in Energy Studies: Exploring Supplies, Constraints and Strategies*, Porto Venere, May 23-27, 2000.

- Foran, B. (2009). *Powerful Choices: Transition to a Biofuel Economy in Australia*. Land and Water Australia Research Report CSE5, July 2009, 316 pp. <http://lwa.gov.au/files/products/innovation/pn30178/pn30178.pdf> accessed 7-9-2010
- Garnaut R. (2008). *The Garnaut Climate Change Review Final Report*. Cambridge University Press, Cambridge UK 680 pp. <http://www.garnautreview.org.au/index.htm#pdf> accessed 7-9-2010
- Hall, C., Tharakan, P., Hallock, J. Cleveland. C. and Jefferson M. (2003). "Hydrocarbons and the evolution of human culture". *Nature* 426,318-322, 20 November 2003.
- Herring H. and Sorrell S. (2009). *Energy Efficiency and Sustainable Consumption: The Rebound Effect*. Palgrave Macmillan, Basingstoke UK, 266pp.
- Kümmel, R., Henn, J. and Lindenberger D. (2002) "Capital, labor, energy and creativity: modelling innovation diffusion". *Structural Change and Economic Dynamics* 13,415-433.
- Lawn P. and Clarke M (2010). "The end of economic growth? A contracting threshold hypothesis". *Ecological Economics* 69,2213-2223.
- Levallois C (2010). "Can de-growth be considered a policy option? A historical note on Nicholas Georgescu-Roegen and the Club of Rome." *Ecological Economics* 69,2271-2278.
- MacKay, D.J.C. (2010). *Sustainable Energy – without the hot air*. UIT Cambridge UK, 383pp. <http://www.inference.phy.cam.ac.uk/sustainable/book/tex/cft.pdf> accessed 7-9-2010
- Madlener R. and Alcott B. (2009). "Energy rebound and economic growth: A review of the main issues and research needs". *Energy* 34,3,370-376.
- Mallon K. and Hughes M. (2008). *Industrial Constraints and Dislocations to Significant Emissions Reductions by 2050. A Climate Risk Report* prepared for WWF Australia, 2008 111pp. <http://www.climate-risk.com.au/userfiles/image/Download%20Files/wwf/Identification%20of%20industrial%20constraints%20v.20%20with%20schedules%20included.pdf> accessed 14-9-2010.
- Seligman P (2010). *Australian Sustainable Energy – by the numbers*. Version 1.3 Melbourne Energy Institute, University of Melbourne, July 2 2010, 143 pp. http://energy.unimelb.edu.au/uploads/Australian_Sustainable_Energy-by_the_numbers3.pdf accessed 7-9-2010
- Slessor M., King J. and Crane D.C. (1997). *The Management of Greed: A Bio-Physical Appraisal of Environmental and Economic Potential*. Resource Use Institute, Edinburgh, Scotland 334pp.
- Wright, M. and Hearn P. (2010). *Australian Sustainable Energy: Zero Carbon Australia Stationary Energy Plan*. Melbourne Energy Institute, University of Melbourne, June 2010, 171 pp. http://media.beyondzeroemissions.org/ZCA2020_Stationary_Energy_Report_v1.pdf accessed 7-9-2010

SESSION 3.1

SCENARIOS OF ENERGY TRANSITION AWAY FROM FOSSIL ENERGY

Schnitzer H.

NATURAL GROWTH CURVES FOR MODELLING THE TRANSITION TO A POST CARBON SOCIETY

Opstelten I. J., Weterings R., Versteeg F. A.

ENERGY TRANSITION OF A SECTOR IN THE NETHERLANDS

Matutinović I.

INSTITUTIONS FOR ENERGY TRANSITION AT THE PEAK OF THE OIL AGE

Krómer I.

PROSPECTIVE LIFE-CYCLE UNCERTAINTIES OF EMERGING ENERGY TECHNOLOGIES

Sousa C. & Cabugueira M.

OPTIMIZATION PROPOSAL OF THE RES-E SUPPORT MODEL IN PORTUGAL: COMPARISON OF THE PORTUGUESE, SPANISH AND GERMAN MODELS

NATURAL GROWTH CURVES FOR MODELLING THE TRANSITION TO A POST CARBON SOCIETY

*Hans Schnitzer**

*Graz University of Technology, Institute for Process and Particle Engineering,
8010 Graz, Austria*

ABSTRACT

The forecast of technological development is frequently done by exponential models or by technology wedges (linear growth). In reality, most real market penetrations of new technologies follow S-curves with an experimental growth in the beginning and a slower growth later on. Also the transition to a low-carbon society might follow such a curve. At the beginning, changes are difficult and therefore slow. Later on, the changes will gain speed, but they will slow down again, when the goals are nearly reached.

The paper describes the fitting procedures for such curves for the transition of the energy system to a more efficient and renewable one and to the market penetration of renewable energy. A mature market (biomass heating in Austria) and a growing market (world wind power) are analyzed in detail.

Keywords: Renewable energy, models, growth, market penetration, S-curve, sustainability

1. INTRODUCTION

Several political bodies follow the recommendations of scientists and postulate a transition to a post carbon society. There is consent that by 2050 the emissions of greenhouse gases should be reduced by 80% compared with the situation in 1990 (G8 2009, EC 2007). The strategies to achieve this goal are mainly two: a reduction of the total amount of energy needed for the provision of the energy services asked by the society combined with a shift to energy sources with a significantly lower effect on climate change. Apart from this long term goal, there are several intermediate goals defined for 2012, 2020 and 2030.

Many evaluations of the technology options are based on a linear market introduction of new technologies, like the “wedge” approach (Pacala 2004, Socolow 2004), or on an assumption of an exponential growth. In this contribution, the market penetration of new low-carbon technologies is modeled according the s-shaped growth curves known from biological growth and the market penetration of new technologies.

Scientific research findings on climate change and, more than this, political statements of leading politicians and EU bodies demand a further reduction of greenhouse gas emissions beyond 2020 with a target of 20% emissions in 2050 compared to 1990. In July 2009, the leaders of the European Union and the G8 announced an objective to reduce greenhouse gas emissions by at least 80% below 1990 levels by 2050 in the industrialized countries. In October 2009 the European Council set the appropriate abatement objective for Europe and other developed economies at 80-95% below 1990 levels by 2050 (G8 2009, Roadmap 2009).

This ambitious targets need to be translated into a low carbon society with all its social and technological implications.

* E-mail: hans.schnitzer@tugraz.at; Tel.: +43 316 876 7464

2. FORECASTING IN ECONOMICS AND TECHNOLOGY MARKETS

In most cases, forecasting of developments uses exponential growth rates (J-curve) or linear models (Technology Wedges). The models can be time-oriented or value-oriented (Philipson 1978).

2.1. The concept of technology wedges

While most economic forecasts base on exponential growth expectations (J-curves), in order to assess the potential of various strategies to reduce the energy demand, the concept of “technology wedges” is used frequently to assess the future potential of technologies. In J-curves the growth is always proportional to its current size.

The difference between the inclining path of energy demand currently predicted (BAU – business as usual) and the flat path from the present to the future urges a triangle of necessary reductions. This “reduction triangle” can be divided into several triangles—or “wedges”—of equal area as shown in figure 1. Globally seen, each wedge should result in a reduction of 1 billion ton of carbon per year by 2050, or 25 billion tons over 50 years. Fifteen carbon-reduction strategies have been examined by Socolow et al., each of which is based on a known technology, is being implemented somewhere at an industrial scale, and has the potential to contribute a full wedge to carbon mitigation. (Socolow 2005, Socolow 2006)

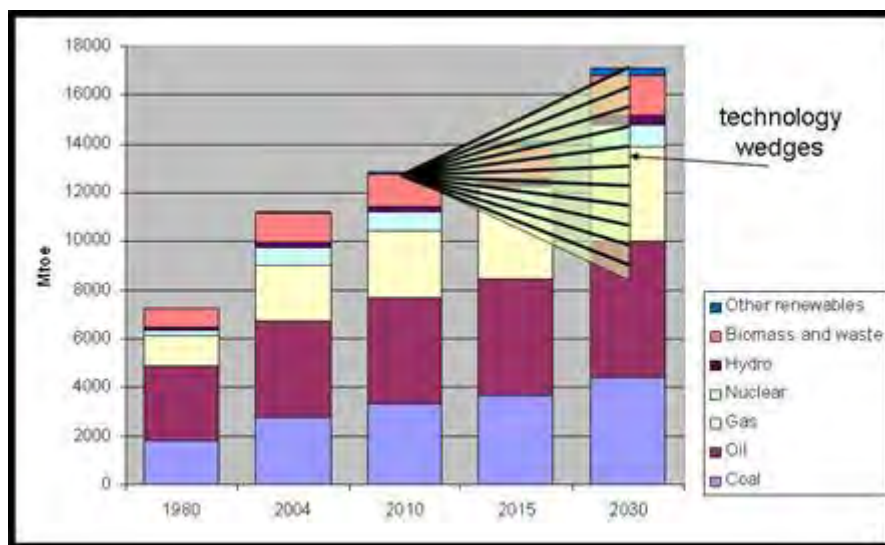


Figure 1. Technology wedges would stabilize and reduce the energy consumption (data from IEA 2006)

Changes are possible in energy services, application technologies and transformation technologies at a given life style. Only a few technologies will fulfill the requirements for wedges.

In Austria, a group of researchers under the lead of WIFO is working on the design of technology wedges that will be able to meet Austria's national GHG targets. For Austria a wedge should have the size of about 1 GgC. They consider the following sectors:

- Housing and living
- Mobility
- Industry
- Materials
- Transformation technologies in the energy system.

In each of the sectors, a set of wedges has been defined and described according to its technological characteristics and economic potential.

There are several studies for sector specific technology developments. Some of the key findings for the relevant industrial sectors are discussed in the publication of the International Energy Agency “Energy Technology Transitions for Industry - Strategies for the next industrial revolution” (IEA, 2009). According to these analysis global emissions from industry could be reduced by halve compared to the baseline 2005.

CO₂ emissions reductions will be needed from all industry sectors. But action is particularly crucial in the five most energy-intensive sectors: iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium (comp. figure 2.).

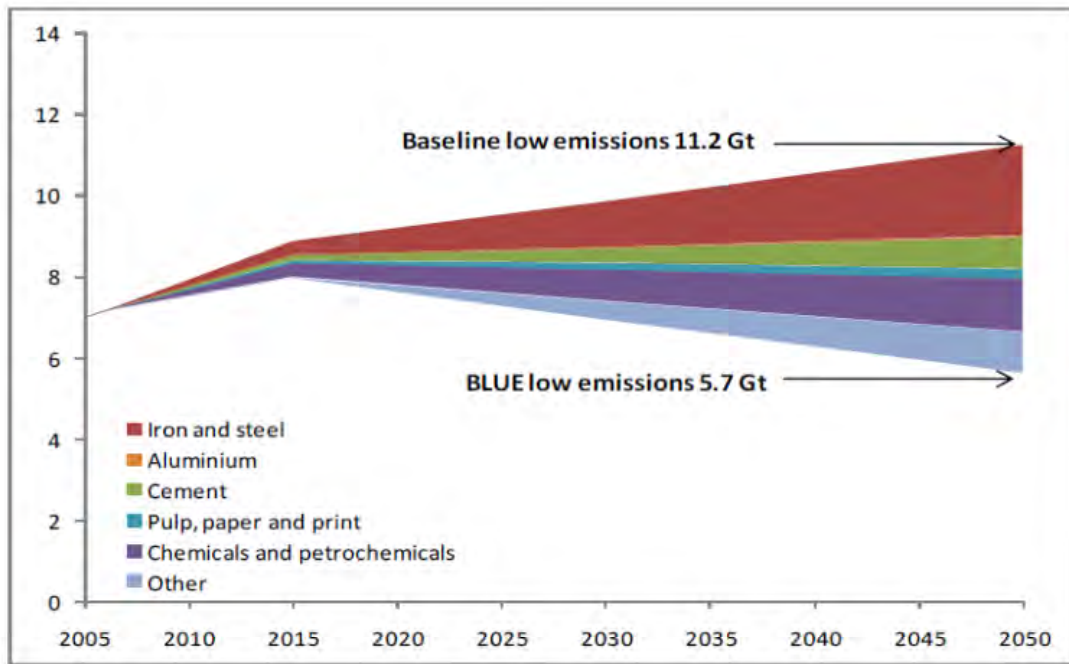


Figure 2. Contributions of the main industrial sectors to a reduction of global GHG emissions (IEA 2009).

Not depending on the industrial sector, there are four different approaches to reduce GHG-emissions (figure 3):

- Recycling and energy recovery, including the utilization of secondary raw materials
- Energy efficiency including all other approaches of process innovation and process intensification
- Fuel and feedstock switching to renewables and carbon neutrals
- Carbon capturing and sequestration

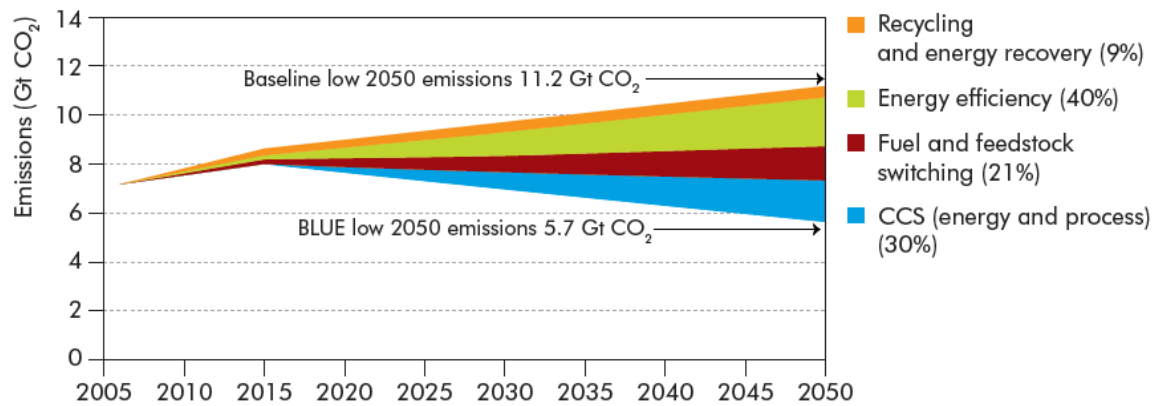


Figure 3. Approaches for reducing direct CO₂ emissions from industry, 2006 to 2050 (IEA 2009).

According to the International Energy Agency, the first three approaches could stabilize the emissions and only CCS as an additional technology can reduce the emissions.

Modeling the development with wedges leads to problems in the long term. This approach includes the risk of ending up with negative numbers and more than this, it requires large changes in an instant and it does not allow learning and a development of a market.

2.2. Logistic S-growth curves as a model for market penetration of new technologies

Using wedges, no long term forecast possible. It is also a fact, that new technologies do not penetrate markets in a linear way. Usually there are at least three phases (comp. fig. 4):

- an innovation-phase with slow growth (lag phase)
- a growth phase with nearly exponential growth (log phase), and
- a maturity phase with declining growth at the end of the economic life time of the technology: growth stops at maturity.

Typically in the “innovation phase” of the S-curve, these unfamiliar products are expensive and downright difficult to use. Once the product hits the critical mass of around 10 per cent market share, we see the beginning of the “growth phase” of the S-curve. After it achieves 90 per cent market share, growth slows and the product enters its maturity phase. At this point, the most conservative consumers begrudgingly adopt the product.

While the S-curve is a great tool for predicting the acceptance of new technology, it even predicts the popularity of social trends. The Green movement, for example, began with a small, marginal group of environmentalists in the 1960s. The first Earth Day in April 1970 consisted of ragtag demonstrations that selectively made the news, but environmentalism didn't start becoming a popular phenomenon until the late 1980s. Thirty years later Time Magazine devoted an entire special edition to the green movement, entitled Earth Day 2000 and distributed it worldwide (<http://www.hsden.com/s-curve/>). Similar models have been used for forecasting the telecom market (Stuck 2007) and for war events (Marchetti 1992).

For the description of an s-curve four parameters are needed:

- The minimum value v_{min} at the beginning of the project (usually zero, as in figure 4)
- The maximum value v_{max} (e.g. the potential of wind energy or the available biomass)
- The year y_{mean} when 50% of the market is covered
- The gradient a at 50%

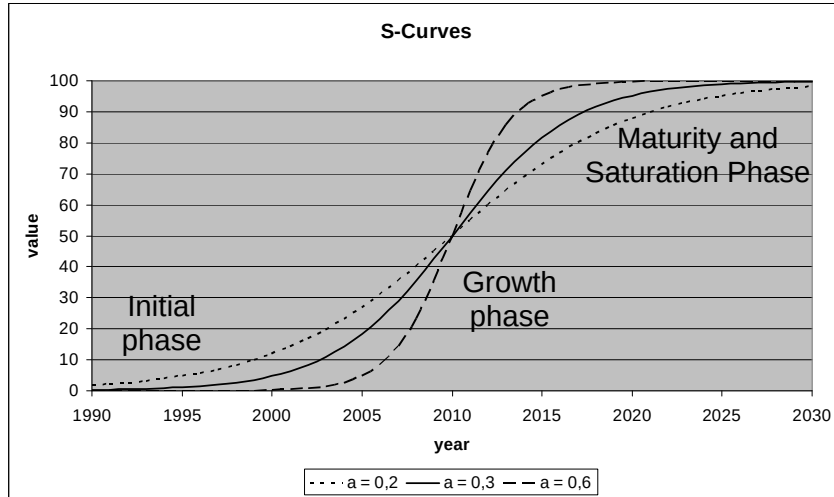


Figure 4. S-shaped growth curves with different inclines at 50% market penetration

The value v in the year y is calculated by:

$$v = v_{\min} + \frac{(v_{\max} - v_{\min})}{1 + e^{(-a*(y - y_{\text{mean}}))}}$$

The four parameters can be found by a numerical minimization of the squares of the difference between the actual and the calculated values for all data.

$$\sum_i (v_{i,\text{actual}} - v_{i,\text{calc}})^2 = \min$$

The value for $v_{\max}$ can change through time, depending on technological developments (higher efficiencies) or changed environmental conditions (prices, legislation, public acceptance, changed subsidies, ...).

The gradient defines the annual change and has a maximum at 50% ($v = v_{\max}/2$) of the market potential $v_{\max}$. A higher value for a describes a faster market penetration. From the management point of view, the market chances at the year y_{mean} from a growing market to a competitive one. Its deviation gives a bell-shaped curve as shown in figure 5 (dashed line).

It can be assumed that the transition to a new low-carbon system will follow an S-shaped curve like any market penetration of new technologies. Analyzing the European targets on CO₂-emissions, it can be seen, that they fit quite well. The following emission targets have been put under:

1990: base year = 5,231 Mt = $v_{\max}$
 2012: -8%
 2020: -17%
 2050: -80%

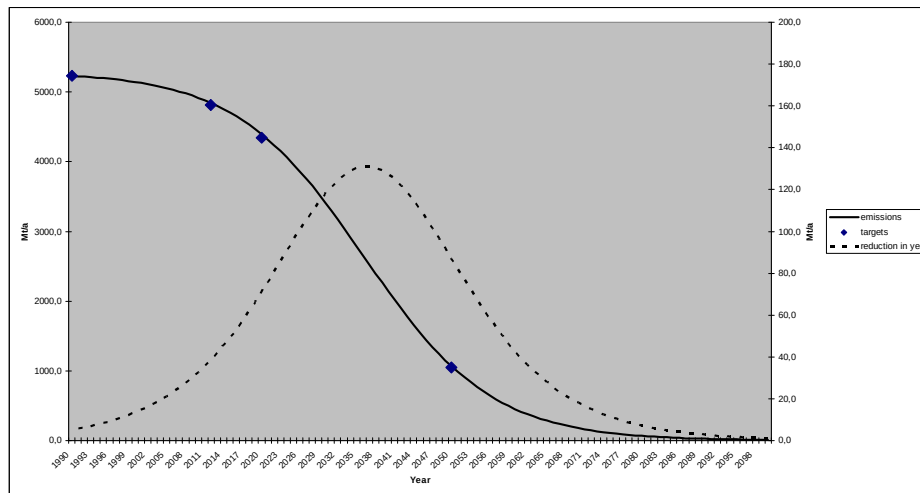


Figure 5. S-shaped scenario for CO₂-emissions reduction in Europe (Tg/a = Mt/a)

$v_{\min}$ was fixed at zero, assuming that finally, in an infinite future, the system will be CO₂-neutral. Highest reductions are necessary in the years 2036 and 2037 with 130.7 Mt/a (bell shaped dotted curve, right axis). In the beginning the necessary achievements are rather low, as they are in the end. So there is time to convince people and industry to change as well as to develop new technologies. As soon as business and consumers take up the new ideas, the market will accelerate. At the end, the potential for further reduction shrinks and the reductions get smaller as well.

Figure 6 shows the reduction goals for Austria (triangles). 2012 (-13% with the base year 1990) and 2050 (-80% as an ambitious target) are exactly in line with such a course (left axis). The highest annual reductions of about 1.64 million t CO_{2e} will be necessary in 2033 (dashed line, right axis). This value has been reached in some years before (diamonds) and is obviously achievable. After 2040 the further potentials for a reduction are declining.

As can be seen (stars), actual reduction rates in the years between 1990 and 2008 were mostly below zero (which means, the emissions increased), with only few exceptions. No clear development or a steady reduction path as a result of systematic policy measures and regulation can be seen. The observable increase in emissions since the base year 1990 demands from Austria to put more emphasis on effective reduction measures (diamonds).

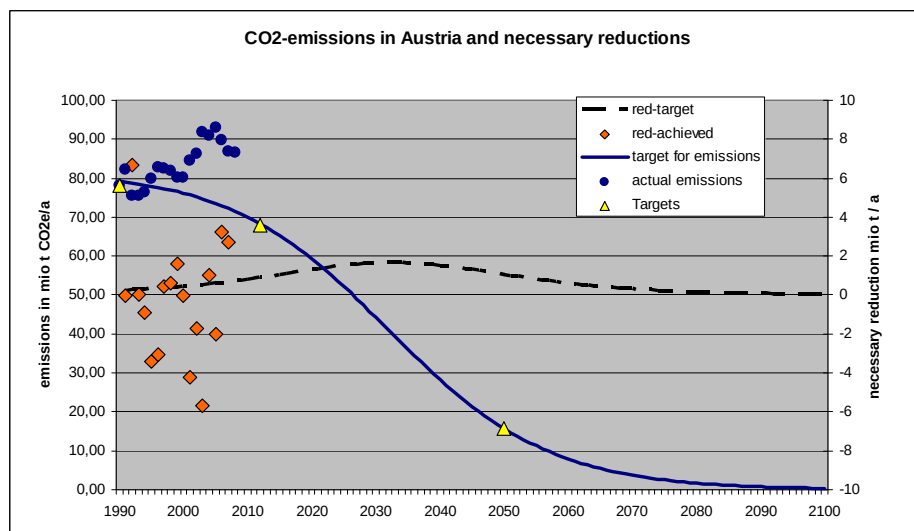


Figure 6. Necessary reduction path till 2050 for Austria (Source: own calculations)

These calculations are based on a constant delivery of energy services without a growth in demand or a reduction through efficiency measures.

The influence of a change in total energy consumption can be demonstrated on the necessary amount of renewable forms of energy (REs) in Austria. Austria has a goal of 34% renewables in 2020 and two possible targets for 2050: 50% according to the national plans, 80% according to the postulation of scientists and progressive politicians (large squares in fig. 7). The actual percentage of renewables in Austria is given by the small squares from 1970 to 2009.

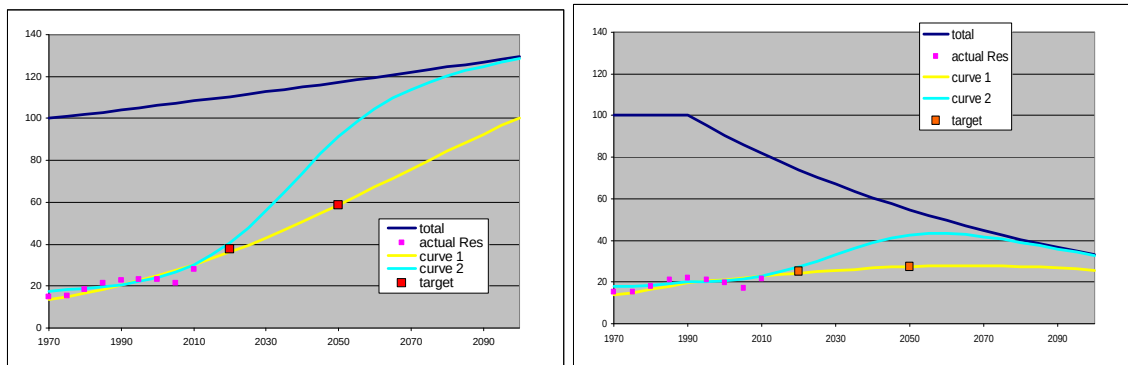


Figure 7. Necessary increase of renewables in two scenarios in Austria

If a yearly increase of only 1% in energy consumption is expected (left diagram in figure 7), REs have to cover the whole present demand in 2056 (80%) or 2100 (50%) alternatively. If an annual reduction of 1% in the demand is achieved, the maximum amount of renewables has to be supplied in 2055 with 43% respectively 28% of the present consumption. In the later case, almost no increase of the total energy provided by REs has to be achieved. The goals are reached by reduction measures only.

3. FORECASTING TECHNOLOGY DEVELOPMENTS

Modeling the past developments of selected technologies (biomass heating, biodiesel, wind, PV,...) it can be seen, which technologies develop according to undisturbed market conditions and which are boosted or hindered by a change in political or economic environment.

3.1. Modeling in a mature market

In the recent years, the market for biomass heating systems boomed in Austria. Several thousands of units have been installed with an average size of 30 kW (Biermayr 2010). Following rapid technological innovations in the 90ties, the systems are now close to maturity. At the same time, there is obviously an upper limit for such heating systems given by the number of houses and villages on one hand and the available biomass (wood chips, pellets) on the other. At the same time there is a strong development towards low-energy houses which reduces the market for biomass district heating systems and wood chip ovens in single family houses.

Modeling the S-curves for the number of installation and for the power installed results in about the same numbers. Since 2007 the growth rates are declining; the market switches from a growth-market to a competitive one.

The maximum market is modeled with 416,000 plants (~1 plant per 20 inhabitants of Austria) with a total power of 12,700 kW. These data correspond very well with the estimated resource potential for forest biomass plus wood processing residues of 180 PJ/a (Kranzl et al. 2008).

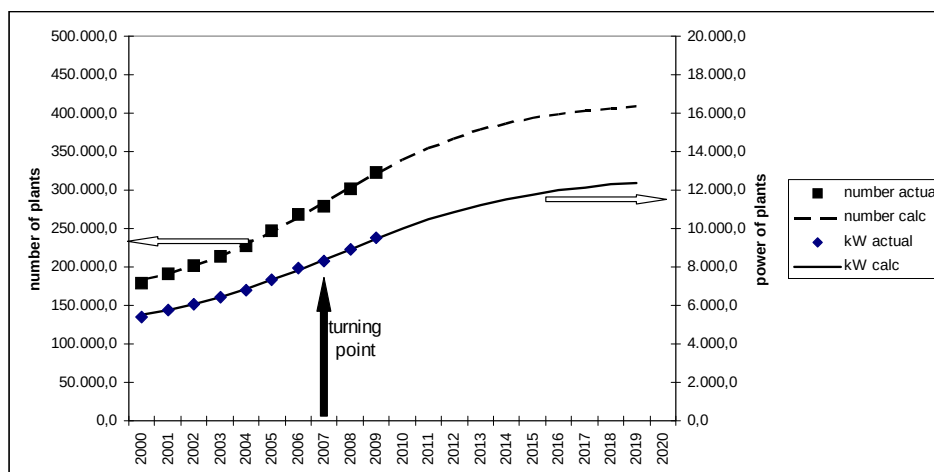


Figure 8. Modeling the market development of biomass heating systems in Austria

3.2. Modeling in a growing market

The relevance of the model for forecasting a technology has been tested with the global wind energy market. Three models were compared:

- Exponential growth
- S-curve without limited potential
- S-curve with limitation to estimated world potential

Data are taken from the World Wind Energy Report (WWEA 2010) for actual data and from Archer (Archer 2005) for the global potential.

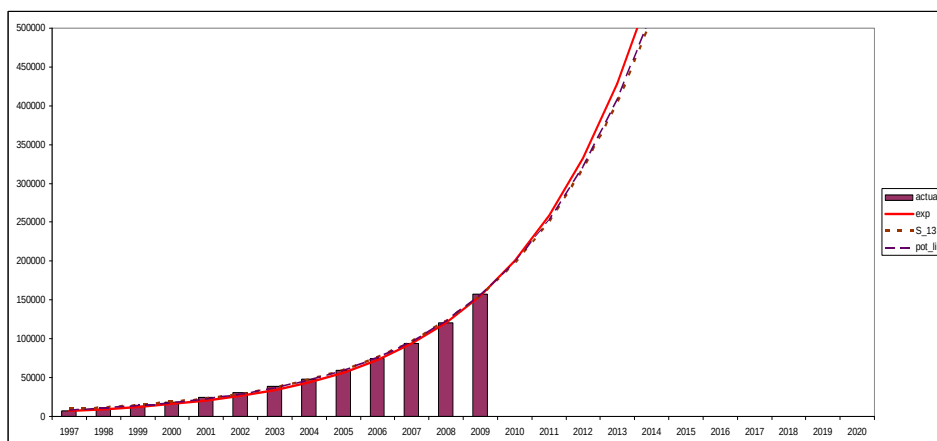


Figure 9. Modeling the global wind energy installations

The results of the calculation show that wind energy is globally seen still in a very early stage of development. The three models hardly differ for these data based on 13 years. The fit with the exponential growth gives a yearly increase of 28.8%. For the models on S-type growth the maximum growth rate, where 50% of the potential is reached, is around 2030.

A sensibility analysis of the model can be made if the fit is based on less data. The more data are available, the higher the final value I estimated. The mean year is also moving towards the value of 2030 while the curve is flattening out.

It becomes obvious that in such an early stage of development all forecasting models have their limits:

The exponential growth model gives an unrealistic long term forecast
 The s-curve model without an upper limitation is too sensible on changes in the environment (change of technical and/or economic constraints)
 The s-curve with a fixed upper limit shows good result and reliable forecasts
 The wedge-approach with a linear development over time fits least.

4. SUMMARY AND CONCLUSIONS

In the beginning of a market penetration of new technologies, J-curves and S-curves are very similar and based on only few data, no decision about the better model can be made. If out of physical or political reasons a limit for the highest uptake of the technology can be made, the S-curves gives much better estimation.

S-curves can be used for political goals, like the development of GHG-emissions, where there are limitations (ZERO-emissions). Compared to a linear approach model, the results needed in the beginning are lower

REFERENCES

- Archer C.L., Jacobson M.Z. (2005): "Evaluation of global wind power". *Journal of Geophysical Research*, Vol. 110, D12110, doi:10.1029/2004JD005462
- Biermayr P., Ehrig R., Strasser C., Wörgetter M., Prügler N., Fechner H., Nurschinger M., Weiss W., Eberl M.: "Innovative Energietechnologien in Österreich" - Marktentwicklung 2009. *Berichte aus Energie- und Umweltforschung* 15/2010. Vienna
- European Commission, 2007, "Towards a Post-Carbon Society", in: *Proceedings European research on economic incentives and social behaviour* Brussels (B), October 2007
- G8 (2009). Responsible leadership for a sustainable future, §65. L'aquila summit 2009.
- IEA – International Energy Agency (2006), *World Energy Outlook 2006*, International Energy Agency (IEA), Head of Publications Service, Paris France.
- IEA - International Energy Agency (2009): *Energy Transitions for Industry. Strategies for the next industrial revolution*. Paris
- Kranzl L., Haas R. (2008). "Strategien zur optimalen Erschließung der Biomassepotenziale in Österreich bis zum Jahr 2050 mit dem Ziel einer maximalen Reduktion an Treibhausgasemissionen". *Berichte aus Energie- und Umweltforschung* 52/2008, Vienna
- Marchetti C. (1992): "A simple mathematical model of war events". *Historie & Mesure* VII-3/4, 297-312
- Pacala S., Socolow R., (2004). "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies", in: *Science*, American Association for the Advancement of Science, 305 (5686) Washington, 968-972
- Philipson L.L. (1978): "Market penetration models for energy production devices and conservation techniques". *Technological forecasting and social change* 11,223-236
- Roadmap 2050 (2009) project is an initiative of the European Climate Foundation (ECF) and has been developed by a consortium of experts funded by the ECF. The work on the three volumes of the Roadmap 2050 project has been undertaken by:
 Volume I: *Technical and Economic Analysis*: McKinsey & Company; KEMA; The Energy Futures Lab at Imperial College London; Oxford Economics and the ECF
 Volume II: *Policy Report*: E3G; The Energy Research Centre of the Netherlands; The Regulatory Assistance Project and the ECF
 Volume III: *Graphic Narrative*: The Office for Metropolitan Architecture and the ECF
- Socolow R., (2005). "Stabilization Wedges: Mitigation Tools for the Next Half-Century", in: *Proceedings Avoiding Dangerous Climate Change*, Exeter (UK), February 2005
- Socolow R., Hotinski R., Jeffery B. Greenblatt J.B., Pacala S. (2004). "Solving the climate problem - Technologies available to curb CO2 emissions", *Environment* 46 (10), 8–19
- Socolow R.H., Pacala S.W (2006). "A plan to keep carbon in check". *Scientific American* Sept. 2006, 50-57
- Stuck B., Weingarten M. (2007): *There's an s-curve down the road for xTCA market*. Business Communication Review, Nov., p 50-54
- WWEA - World Wind Energy Association (2010): *World Wind Energy Report*. Bonn March.

ENERGY TRANSITION OF A SECTOR IN THE NETHERLANDS

I.J. Opstelten, R. Weterings, F.A. Versteeg*

Energy research Centre of the Netherlands, TNO, FORGOOD

ABSTRACT

To realize the energy transition in the building sector, three types of obstacles have to be overcome: technology-related, process-related and integration of technology and process. To this end an innovation-implementation program has been constructed. The intrinsic driver of the program is the realization of increasingly more ambitious energy concepts in three successive waves, allowing for the different actors to learn from the previous wave, to prepare for the next wave and to scale up these type of projects both in terms of quantity and quality. The establishment process of the program identified a key success factor for the transition process itself: the role of the individual.

Keywords: Energy transition, building sector, innovation, individual

1. INTRODUCTION

Today's society is completely dependent on energy, be it for the industrial sector to produce products, the transport sector to enable mobility or the built environment to provide buildings with thermal comfort and enable the use of electric appliances. This dependence on energy comes at a price, stemming from our need of security of supply and the necessity to minimize the negative impact on the environment. These issues demand a fundamental change of the way our society is build around the current energy system. Such a process of change in a complex societal system is referred to as a transition [de Haan, 2010]; in this case a transition to a sustainable society, or more specific an energy transition.

Considering the many technological and non-technological challenges to be addressed in many different sectors, the Dutch government realized that no department could tackle this task single handily. Thus in 2006, an Interdepartmental Program-bureau Energy transition (IPE), was formed in the Netherlands. Next, energy transition platforms were installed around several key technologies for the realization of the sustainable future. In each energy transition platform, professionals (a titre personnel) with their roots in industry, R&D or policy making were given the task to formulate the requirements and/or solutions for the part of the energy transition that their platform covers.

2. TECHNOLOGY TRANSITION VS SECTOR TRANSITION

Both in the Netherlands as well as on European scale, the use of primary energy is more or less equally divided between three sectors: Industry, Transport and the Built Environment. Energy use in both the industrial sector and the transport sector are dominated by a limited set of technological systems. Therefore, it is not surprising that the first energy transition platforms formed, were mainly technology driven (e.g. Sustainable Mobility, New Gas, Renewable Electricity Provision, etc.).

* Corresponding author; E-mail: Opstelten@sev.nl; Phone: +31623291616

It was realized, however, that technology driven platforms, would not cover the challenges of all sectors. Thus a specific platform for energy transition of a complete sector was installed: the platform for energy transition of the built environment: PeGO.

The platform itself is formed by individuals with their roots in different actors of the building process, such as project development, contractors, manufacturers in the supply chain, local authorities, housing corporations and research, lead by the former minister of economic affairs Jan Terlouw.

It is a common misconception of engineers, that technology push (leading to market push) can bring about a sustainable society. On the other hand, it is also a misconception (often heard from politicians), that consumer demand (leading to market pull) will automatically provide the solutions for a sustainable society and implementation thereof. Considering the available technology, with which today already an energy neutral building can be constructed, this is apparently especially true for the built environment. The reason for this is twofold:

1. An energy neutral building, district or built environment, consists of a whole range of technologies, which interact with each other and influence not just the energy signature but also other important functions (health, comfort, maintenance, etc.)
2. The end users and the building sector itself are not homogenous in their vision on sustainability and their related behaviour reflects this.

To illustrate the second point, following McCall's [McCall, 1994] analysis of school students, the following types of market actors can be discerned, linked to their approach to innovative developments:

- Front Runners: these actors seek and even provide new developments and experiment with new technologies, driven by a desire to profile themselves.
- Early Adaptors: these actors are motivated to implement new developments because of the promise of improvement, but seek actively for foundation of the claims.
- Early Majority: these actors, having seen foundation for claims in practice on relatively small scale, will seek for safe adaptation of the new developments.
- Late Majority: this group essentially waits for 50% of the market to take up the developments, before they deem them as sufficiently proven.
- Laggards: these actors are only motivated to take up new developments when obliged through laws and regulations.

This, in combination with the large amount of actors (designers, project developers, builders, maintenance, owners and users) involved, together determining the energy performance of a building, illustrates the need for a sector approach to energy transition in the built environment instead of a technology transition.

3. PLANNING FOR ACTION, ACTION IN THE PLANNING PROCESS

3.1 Planning for action

The first step to realize a sector transition is to bind the actors around a single vision. Interestingly enough it was the result from an energy study from 2006, presented early 2007 [Opstelten, 2007], that provided a common goal: the realization of an energy neutral built environment in the Netherlands in the middle of this century. The study was centred around the substantiation of the maximum realizable potential for primary energy reduction in the built environment. Here, the maximum realizable potential refers to that part of the technological potential as defined by Blok [Blok, 2006] which can be realized within a given time frame, thus taking into account the speed of development and implementation of technological innovations. The study analyzed this potential by assessing the energy improvements which can be realized at natural mutation moments

(demolition, new additions, renovation, large maintenance and HVAC system replacement) of elements in the built environment, between 2005 and 2050. The result is shown in Figure 1, which was used by both market and policy actors as the visualization of the common goal. Not just because of its contribution to the energy challenges of the society, but also because it could position the built environment, despite its traditional appearance, as the most innovative sector of this century.

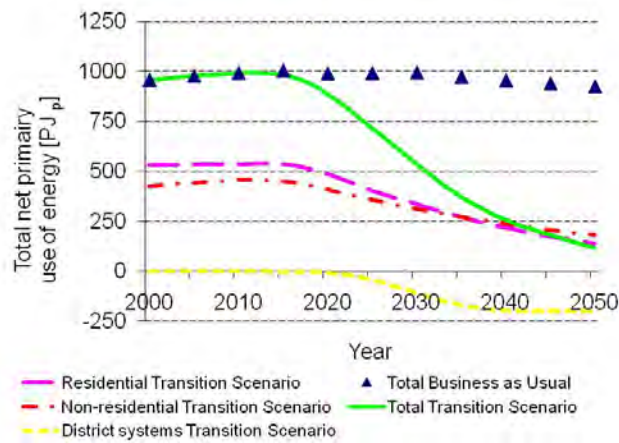


Figure 1. Overall result from the energy study, indicating the contribution of different elements of the built environment on the road to an energy neutral built environment in 2050.

When the energy transition platform for the built environment was formed, the members were challenged to formulate concrete initiatives to enable the sector to transform itself to a sustainable one. The following plans resulted, linked to the types of market actors described in the previous chapter:

1. Regulation, focused on removing legislative obstacles or omissions to stimulate the energy transition of the sector. This has a direct relation to the “late majority” and the “laggards”.
2. More with Less, focused on acceleration in the renovation sector of the adoption of cost-effective energy concepts. This is often referred to as “Making Meters” and focused on the “early majority” and the “late majority”.
3. Innovation, focused on the development of integral concepts and systems for buildings and/or communities with high energy ambitions, such as energy neutral buildings and factor 5 renovation (-80% CO₂-reduction) concepts. This is often referred to as “Preparing Meters” and focused on the “innovators” and “early adaptors”.

For all initiatives, the total energy consumption for the built environment is taken into account, building related *and* user related energy. This in itself is a major change in the way the actors in the building chain have approached the subject of energy. Up to now, both in the Netherlands and elsewhere, actors in the building chain were only concerned with building related energy (mainly for HVAC and domestic hot water), expressed in an energy performance indicator. In the Netherlands since 1995, every new building designed was obliged to conform with a minimum energy performance, indicated by the EPC-value (Energy Performance Co-efficient). This value addressed all building-related energy use (space heating, domestic hot water and auxiliary energy for HVAC systems). In 1995 the EPC value was set at 1,4 and at that same time policy was announced which would ensure successive tightening from 1,2 in 1998 and 1,0 in 2000. The announcement of these successive steps in 1995, rendered a boost to innovation, albeit restricted to pure technological innovations. It took until 2006, when energy transition took hold and stricter demands were formulated at European level, through the EPBD, the EPC was further

tightened to 0,8 and policy was announced for consecutive steps to finally reach an “energy-neutral” new building demand in 2020. These successive steps, however were still only focussed around building related energy, whereas at an EPC of 0,8, the user-related energy in residential buildings is at the same level as the building related energy, whereas the former has shown a trend of increase, rather than decrease. This illustrates the importance to set standards for the total energy used in the building, if the complete potential of the built environment, identified by Opstelten [Opstelten 2007], is to be harvested.

3.2 Action in the planning process

Early on, the innovation working group of PeGO identified the key elements of the Innovation program were identified, illustrated in Figure 2. Creation of three successive energy ambition levels for buildings, within a timeframe of 5-6 years, by co-operation between thinking teams (yellow), doing teams (red) and scaling up teams (blue) and continuous knowledge disclosure.

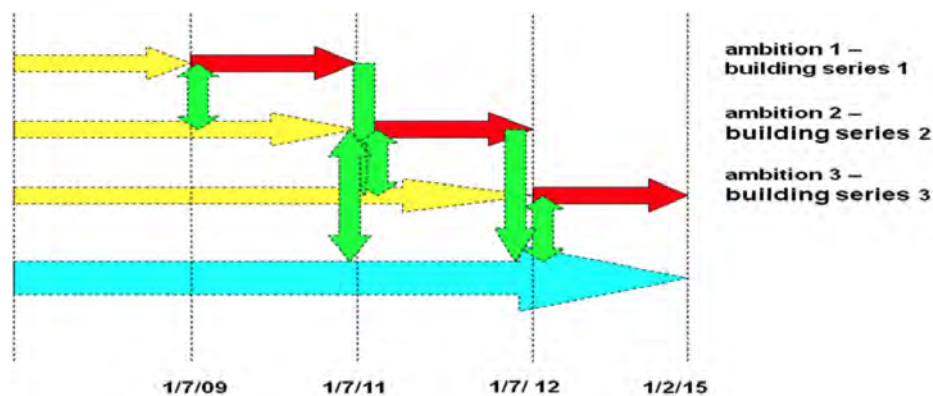


Figure 2. Creation of three successive energy ambition levels for buildings, within a timeframe of 5-6 years, by co-operation between thinking teams (yellow), doing teams (red) and scaling up teams (blue) and continuous knowledge disclosure.

The concrete results of the program, would be the realization of increasingly more ambitious energy concepts in three successive waves, allowing for the different actors to learn from the previous wave, to prepare for the next wave and to scale up these type of projects both in terms of quantity and quality.

The methodology applied to all activities of the innovation program, consists of three types of activities:

- “Thinking” carried out by Innovation teams, with contributors from R&D organizations and actors in the supply chain. These are focused on co-development of new technologies and integral concepts.
- “Doing” carried out by realization teams, with contributors from project development, housing corporations, local authorities and engineers. The concepts, conceived in “Thinking”, will be materialized in lead-market numbers, typically several hundred up to a thousand per wave.
- “Scaling up” carried out by promotion and dissemination teams, with champions from the above-mentioned organizations. These are focused on a multiplication of the successful concepts and a realization of clear demand articulation by end-users for the concepts and the underlying technologies, thus creating the required boundary conditions for a mass market.

While the innovation working group of PeGO was still in the planning process for the creation of the Innovation program, the Dutch ministry of Housing, Communities and

Integration (WWI), enabled the startup of a subsidy scheme for the residential sector early 2007. They asked members of PeGO to help setup this subsidy scheme in line with the first sketches of the PeGO innovation program, working together with the traditional actor in such cases, the energy agency Agentschap.nl. Obviously, this gave an unique opportunity to ventilate the novel approach of PeGO to the larger audience. Although it meant using an existing instrument, which was not designed for the type of innovation experiments, that were sought after by the PeGO innovation working group, this opportunity was welcomed because it could accelerate the initiation of the sector transition. After all, the reaction of public and private actors, for whom the instrument was meant, could help indicate the readiness of those actors to start working from a new paradigm.

That it indeed requires a paradigm shift, became clear when the deliberations between the members of the PeGO working group and those from the energy agency started. The members of the energy agency uttered many concerns with respect to accession criteria, such as:

- the use of total energy usage as a criterion for admission,
- the height of the energy ambition itself (45% lower than that of reference buildings in 1990), implying a stricter demand than that of passive houses,
- the introduction of so-called building-related user appliances energy usage besides conventional user appliances energy usage. With the former, the applying consortia would be challenged to come up with novel approaches to help reduce energy usage by household appliances with building measures and/or building system measures,
- the demand that each project should at least realize 50 residential buildings or apartments,
- public-private consortia as applicants instead of, traditionally, private parties only.

These concerns all reflected the general belief that the market was not ready for such an approach. It was assumed that this combination of novel demands, would result in a very limited amount of applicants and the resulting need to approve also low quality plans. To overcome some of the concerns, a considerable effort was put in the process of formulating the exact subsidy requirements. This process took 6 months. Next it took another 6 months before the actual subsidy scheme, requiring the signature of 3 ministers of different departments, was launched. The subsidy scheme, UKR NEW would allow for 10 winning projects. Thus, in the order of 20 applicants were hoped for; 43 resulted: a huge success. Later on, in 2009, a similar scheme was used to address the non-residential sector: the UKP NESK which proved to be an even larger success.

4. INNOVATION MOTOR APPLIED TO A SECTOR

Innovation is considered to be an individual and a collective process. The determinants of (technological) choices are not only originating from the different market actors but of the entire “innovation system”. The potential for a successful innovation is directly related to the way the (technological) innovation system functions. This the reason why market actors, public institutions and knowledge institutions need to contribute actively to improved functioning of the required innovation system. Hekkert and Ossenbaard [2010] have described a system of 7 functions which together determine the speed of adaptation of an innovation in practice, referred to as the Innovation motor, illustrated in Figure 3 and described in Table 1. A more detailed description of the different functions and type of events associated with them can be found in [Suurs, 2009].

This concept was used by IPE in the second half of 2007 to assess the proposed activities for each of the innovation programs set forth by the different energy transition platforms and identify the main barriers. Since this concept was constructed for the evaluation of the process around the creation and implementation of single technologies,

a first attempt to assess the innovation program for the built environment was constructed around the evaluation of the implementation of solar collectors and the passive house concept. Although the latter at least surpasses the level of a single technology, it still was in its evaluation completely technological driven. This was seen as a limitation, since the innovation program for the built environment was setup to realize a sector transition instead of a technology transition as explained earlier.

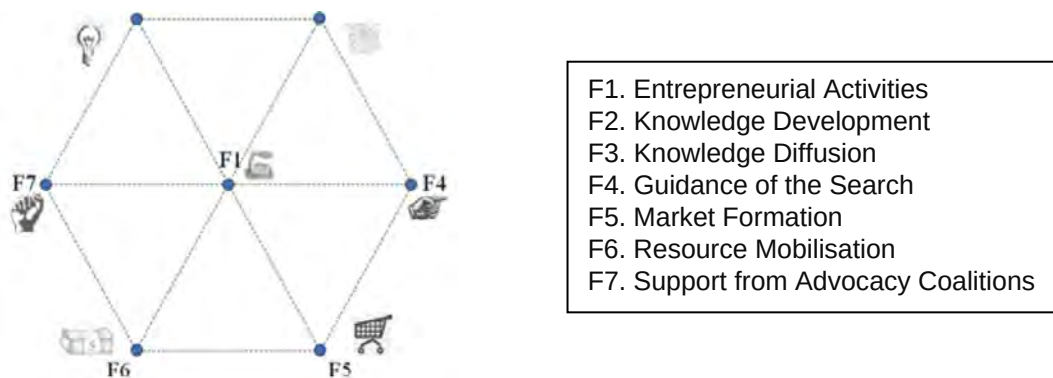


Figure 3. The Innovation motor and its functions.

For this reason, a second assessment was performed for the Innovation program proposed by PeGO in the first half of 2008. In this second assessment the end vision of an energy neutral built environment, to be realised in the middle of this century, was the starting point and three types of barriers were identified blocking the route to it: Technological barriers, Process barriers and Barriers resulting from the integration of technology and process. These barriers now form the basis for activities set out in the resulting “Energy Innovation Agenda - The Built Environment”, adopted by the WWI Ministry early 2009. The final hurdle before actual execution could take place, was the creation of a steering team within an organisation fit for the type of experiments to be set up. Early 2010 this hurdle was taken with the assignment of the execution program to the SEV foundation and the recruitment of a management team dedicated to this program.

5. LEARNING DURING THE PROCESS

To realise an energy transition in the building sector in the long run, incremental adaptations and improvements of existing energy systems will ultimately fall short. Instead, radical new energy systems need to be introduced: new ways for people and companies to meet their energy requirements for comfort, power and light. As we pointed out earlier, this is not simply a matter of technical innovations, but also of developing the associated infrastructure, institutions, socio-economic environment, governmental policies and fostering appropriate behaviour of companies, consumers and NGO's. There is no blue print for the innovation programs needed in support of such a sector transition. Actually the development of the PeGO innovation program proved to be a process of learning by doing.

In order to support this learning during the process, PeGO has made use of so called Learning Histories. The methodology of Learning Histories has been developed by researchers from the American research institute MIT. Working with learning histories is similar to exchanging experiences through story telling. Important in learning histories is that they describe an important experience within its' context. Actually a learning history is a story with three layers: the descriptive layer giving a summary of the actions and events, the perception layer conveying how the people involved perceive what happened and the reflexive layer with questions and observations of outsiders. Combined these three layers

provide an effective means not only to document learning experiences, but also to convey them to other individuals and groups.

The learning history on the development process of the PeGO Innovation program focuses on the period between the first PeGO innovation plan in 2006 and the official start up of the program in 2009. One of the key observations refers to the importance of innovation trajectories, enabling building consortia to work together during several, subsequent phases of in the innovation cycle. It was already in 2006 that one of the members of the PeGO working group on innovation group stated that radical innovations would need more stable partnerships between market actors, knowledge institutions and public institutions. Especially in a sector in which consortia change in each new building project, it was expected that the building up of innovative quality would demand working relationships that last longer than one project. Working together during various phases of the innovation cycle would provide the continuity needed at consortium level to build up experience and operational excellence and a better understanding of the needs of the different actors from each other to be able to fulfil their role in the process optimally. Consequently, the notion of innovation trajectories became important in the PeGO Innovation program. However, the subsidy scheme for the residential sector, started up by the Dutch ministry of Housing, Communities and Integration (WWI), did only allow for trajectory related subsidies. There was no option for securing continuity at consortium level beyond each separate project. So, although using this existing instrument provided the opportunity to accelerate the initiation of the sector transition, it actually did hamper the development of more stable, innovative consortia of building firms, knowledge institutions and public institutions. The learning history on the PeGO innovation program added in putting the notion of innovation trajectories back on the agenda again. It not only re-fuelled the discussion on the strengths and weaknesses of Dutch' subsidy mechanisms, but also gave a boost to developing new instruments that do allow for more lasting, and intrinsically learning, consortia.

The concept of the Innovation motor can also be used to gain some insight in the development of the sector transition in its early stages. In Figure 4, the important events and its impact on the different functions of the Innovation motor are depicted between the start of the process and the current status.

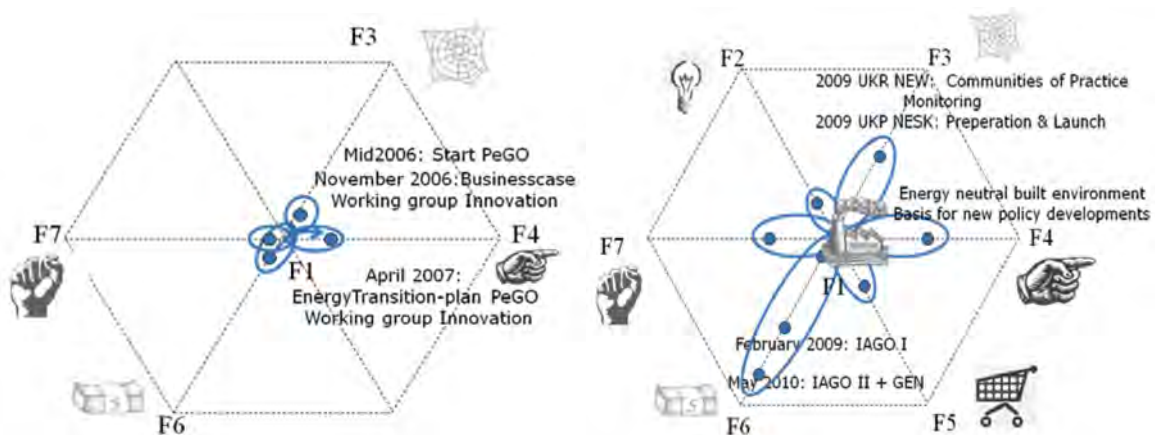


Figure 4. Status of Innovation motor for the built environment sector transition in 2006 (left) and early 2010 (right).

Reviewing the overall process over the last three years the PeGO efforts have especially led to knowledge diffusion, to the development of a shared vision and to the mobilising of new budget from the Government. New activities from private companies and the creation of new markets have been more limited and on the whole implementation

has been more slow then was hoped for at the start. Some lessons from the process over the past years are:

1. Creating the flexible organisation(s) to stimulate the energy transition: The set-up of a strong executing and supporting organisation, needed to facilitate, coordinate, stimulate all efforts concerning the energy transition has unfortunately taken many years. This was basically caused by hesitation from the supporting government, where officials wished to remain within 'old' and 'trusted' organisational forms and subsidy schemes. Creation of support for novel approaches delayed the overall implementation of the programs.
2. Creating new roles and letting go of old role-models: During the past years it has become ever more clear that all parties involved in the energy transition should be willing to give up their old familiar roles and learn new ways of behaviour focusing on the overall targets of the programs and not just on their own interests. By focusing on the interests of the other parties involved the overall program can be realised more quickly and easily.
3. Ensuring long term commitment to the first original targets: In the past three years many initiatives and programs have been developed in the Dutch market. Most of these programs and initiatives have formulated different targets and different approaches. On the one hand the energy transition is been helped by the fact that the transition is becoming more of a movement, on the other hand it has become increasingly clear that programs do not always reinforce one another.
4. Pushing for experiments and creating support from private parties: The majority of private parties have been relatively slow to pick up the transition movement. The group of innovators and quick followers has been relatively small. Knowledge diffusion – even more than knowledge development – has proven to be a key success factor in the whole movement of energy transition in the built environment.

6. THE INDIVIDUAL AS KEY SUCCESS FACTOR

In February 2010, PeGO organised a symposium to launch the Innovation agenda Energy Built Environment. Part of this symposium was a debate led by Jan Terlouw with several actors in the built environment, amongst which the CEO of Volker Wessels, and the former chairman of the NEPROM, the Dutch union of project developers, Dietmar Werner.

During that debate Dietmar Werner was confronted by Jan Terlouw that his current, supportive, views on sustainability in the building sector were almost the complete opposite of the views he proclaimed during his chairmanship of the NEPROM. He replied that “apparently an energy transition cannot occur without a personal transition”. This casual remark holds a fundamental truth about societal transitions, which stem from a need of future generations rather than an acute occurrence. In case of an acute occurrence, like the Dutch flood disaster in 1953, nobody needs to be convinced that something drastic has to be changed, in that case the protection of the coastal provinces against floods.

Climate change, although linked to acute occurrences, is a gradual process, which implies that the direct effects are relatively small compared to the effects on future society, if a transition is not implemented. This implies that everyday life is not affected on the short term, if nothing is changed, and thus the public in general has no acute reason to change their behaviour. This is also the fuel for the so-called vicious circle of blame, see Figure 5, of which a description has been attributed to D. Cadman in [Sustainable Construction Focus Group, 2000].

Figure 5 indicates the apparent strength of institutes (developers, constructors, investors, owners) in blocking the sought for energy transition. The quotes however, give

these institutes a human face and apparent behaviour. The key for the sector transition can therefore also probably be found at this level, the level of the individual.

During the creation process of the innovation program and the adjustment of the subsidy schemes used in the early process, described in section 3.2, this became apparent.

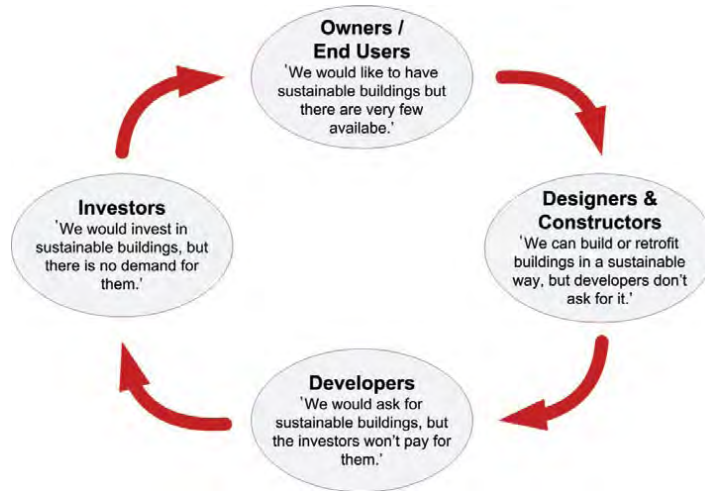


Figure 5. The Vicious Circle of Blame (adopted from Cadman, 2000)

It took individuals, who were willing to seek alternative ways of working to get support for the novel schemes and program. When the second subsidy scheme had to be setup, colleagues of these individuals were made responsible for this task. Notwithstanding the successful launch of the first scheme, all the same concerns were put forward again and it took the persuasion of the former individuals to set aside these concerns and work together towards a common goal.

A second example was the acceleration in the adoption process of the entire PeGO program by the Dutch government. In that case, the personal commitment of individuals of different organisation, stating the required changes not only in the system, but especially in their own organisations, provided the trust that this was not just another way to earn some money, but a genuine attempt to contribute to the realisation of a sector transition. They were subsequently enabled in their efforts and at the same time requested to perform tasks, which traditionally are outside the scope of their function within their organisation. Examples are individuals from knowledge institutes asked to develop a tender subsidy scheme, individuals from governmental organisations to detour hierarchal pathways and walls setup between ministries acting more as entrepreneurs and individuals from building companies to promote an innovation program.

7. CONCLUSIONS

Looking back at the final picture after the energy transition will have succeeded in the future, one can easily believe that all that was needed is the introduction of all those technologies which drive the new sustainable economy. Any transition implies a change of the usual way of doing things. Because, in the case of the implementation of energy transition in the building sector, the required changes imply efforts on the short term, which will have their benefits only on the very long term (decades), an energy transition will not occur when left to the initiatives of market actors. On the other hand, it is also doomed to fail, when market actors are not involved. The same holds for R&D: technological and non-technological innovations, will not deliver an energy transition by itself, although they might be crucial as building blocks for the sustainable society. Finally,

also Policy and Regulations will not bring about the energy transition, whereas without them the incentive for the other actors would be sorely missed.

The only way an actual energy transition will have any chance of success, is when government, market and R&D are willing to join forces to solve this single task and are willing to leave their comfort zone. This is brought about by individuals, having gone through the personal transition, who are in the position to help their organisations to take up the transition challenges, which in turn transcend the organisational barriers and work together towards the realisation of a sector transition.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the representatives from PeGO, the energy agency Agentschap.nl and the ministry of Housing, Communities and Integration (WWI), for their efforts and energy, which enabled the creation of the Innovation program and thus also provide for the personal learning process of the authors.

REFERENCES

- J. de Haan, *Towards Transition Theory* (thesis), *Dutch research institute for transitions (Drift)*, Erasmus University, Rotterdam, 2010.
- J. McCall, *The Principal's Edge*, Eye on education Inc, 1994.
- Opstelten, I.J.; Bakker, E.J.; Sinke, W.C.; Bruijn, F.A. de; Borsboom, W.A.; Krosse, L., *Potentials for energy efficiency and renewable energy sources in the Netherlands*, ECN-M--07-039 mei 2007; 16p., 'Energy Future 2030', Wels, Austria, 2007.
- K. Blok, *Introduction to energy analysis*, Techne Press, Amsterdam 2006.
- M. Hekkert and M. Ossenbaard, *De Innovatiemotor* (The Innovation motor in Dutch), 2010.
- R.A.A. Suurs, *Motors of sustainable innovation. Towards a theory on the dynamics of technological innovation systems* (Thesis). Innovation Studies Group, Copernicus Institute, Utrecht University, Utrecht, 2009.
- Sustainable Construction Focus Group (2000) *Towards sustainability – A strategy for the construction Industry*, CIP, Birmingham.

INSTITUTIONS FOR ENERGY TRANSITION AT THE PEAK OF THE OIL AGE

*Igor Matutinović**

GfK – Center for Market Research. Zagreb, Croatia

ABSTRACT

Only in an environment of high and relatively stable prices of energy can our societies hope to achieve requisite changes in production and consumption patterns that may lead both to energy transition and to reduction of greenhouse emissions. In order to achieve this goal, a society have to impose new constraints on markets in the guise of an import tax on oil and in the removal of subsidies extended to oil industry and to fossil fuels-based electricity generation. If carefully planned, this measure might be accepted by the majority of the population in the advanced Western countries.

Keywords: peak-oil, oil tax, worldview

1. INTRODUCTION

All great socioeconomic transitions in modern history occurred in a context where an established system of values and beliefs was challenged by adverse circumstances and gave way to a new one, usually proposed or supported by elites: the abandonment of the Ancien Régime at the Assembly at Versailles on August 1789, the rejection of the Czarist feudal society in the February Revolution in Russia, the Meiji Restoration in Japan, and up to the collapse of the Berlin Wall. In all these cases the societies in crisis had an already existing model, which their political elites were trying to imitate or adopt. The revolutionary French were may have looked at industrializing, capitalist England and independent American colonies; the Russian liberal and orthodox Marxist politicians had in their minds Western Europe (but failed couple of months later when Lenin, himself bearer of a yet another worldview, took power in October); the elites in Japan had the industrialized West as their model, and the masses of people that ended abruptly the era of the Soviet regime initiated the process of transition to the Western capitalist democracy.

Today, the world is facing its first major energy challenge: conventional oil, our cheapest energy source with highest EROI of all fossil fuels, will eventually peak and then decline in the years afterwards. And there is no available model society to imitate or which tested solutions to adopt in the transition process to post-oil era. Besides that historic inconvenience, there exists another risk, namely that in times of sociopolitical crisis a society finds itself at a bifurcation point at which it may take entirely different pathways: towards adaptation, civilizational deterioration, or collapse. While it is impossible to predict what may happen in such circumstances it is certainly useful to identify scenarios that we would like to avoid at any cost and to explore viable institutional solutions that can work in that direction. This is the main theme of this work.

The great socioeconomic transitions are not limited to political dimension only: they concern any situation in which a change in the boundary conditions – like the availability of energy – triggers a cascade of responsive change in a society. The Western civilization is approaching such a change in the boundary conditions specified in the finite reserves of conventional oil, usually referred to as a peak-oil [Deffeyes 2005]. While the timing of the

* E-mail: igor.matutinovic@gfk.com; Tel: 38514921222

peak-oil and the exact shape of the oil depletion curve is still controversial [Witze 2006; CERA 2006; Zittel and Schindler 2007; Matutinović 2009;] recent empirical studies point that it might be at our doorstep [Alekklett et al. 2010; Owen et al. 2010; Nahawi et al. 2010]: between 2010 and 2014. The possibility of simultaneous onset of climate change and peaking of oil supply represent unprecedented challenges to industrial civilization [Holmgren 2009]. The 2008 edition of World Energy Outlook summarizes the current situation and the challenges that lie ahead in clear and unambiguous terms:

„The world's energy system is at a crossroads. Current global trends in energy supply and consumption are patently unsustainable — environmentally, economically, socially. But that can — and must — be altered; *there's still time to change the road we're on*. It is not an exaggeration to claim that the future of human prosperity depends on how successfully we tackle the two central energy challenges facing us - transformation to a low-carbon, efficient and environmentally benign system of energy supply. What is needed is nothing short of an energy revolution [OECD/IEA 2008, p. 37] “.

While at this moment we are not aware of an immediate “energy revolution” that would replace conventional oil at a similar EROI, we will almost certainly need an institutional evolution and a substantial change in Western life-styles during the transition to post-oil era.² Most probably we will have to review our notion of “prosperity” as well and decouple it from material growth. However, unless we wish abandoning our civilization to the whims of revolutionary storms, of which bitter effects we still keep fresh memories, it is advisable to examine how far we can stretch the present socioeconomic system to meet the aforementioned challenges. Before we embark on that theme it is necessary to provide a system-theoretic framework that will guide the analysis and search for solutions. This is the task of the next section.

2. THEORETICAL FRAMEWORK

According to Salthe [1985] we can represent phenomena in complex systems by using three elementary hierarchical levels in a model: lower level initiating conditions and upper level boundary conditions acting as constraints on a *focal level process*. The system components that act as *lower-level constraints* are generative and propose possible results, while components that appear as *higher-level constraints* are regulatory and dispose – they “dominate” the activities and productivity of focal level processes [Salthe 1985, p.90]. This is possible, among other things, because the rate of change of processes at higher levels is significantly slower than that at lower levels and, therefore, appears to the latter as a relatively constant environment. The model postulates interaction (feedback) between contiguous levels and occasional transitivity across distant levels in the hierarchy. When a bottom-up interaction occurs (as it does in the case of a feedback) it is referred to as a perturbation occurring at the upper level. In the case of transitivity, its effects are diminishing with the distance between the levels and therefore, the hierarchical structure of causality is always preserved (Salthe 1985; 136-143).

The model [Matutinović 2007; 2007b; 2009b] describes a hierarchical direction of causality and constraints that connects worldview, institutions, technologies, and economic activities (figure 1). At the top of the hierarchy there is a prevailing worldview of

² Under post-oil era I do not assume the absolute disappearance of oil from economic usage. I refer to it as to a relatively long period during which the supply of conventional oil, and soon afterwards also of non-conventional oil, will first stagnate for some time (the peak) and then start decreasing at a certain yearly rate, depending on the slope of the depletion curve.

a society, which defines its widely shared values and beliefs³. Within the boundaries of a dominant worldview a society creates and changes its institutional framework and technologies, which then constrain the activities of economic agents at the focal level. In terms of the *specification hierarchy* [Salthe 1993], which looks at the embeddedness of phenomena at the integrative levels of their classes, the hierarchical relation {worldview dynamics {institutional dynamics {economic dynamics}}} means that no radical change in economic sphere is possible unless the institutional framework is changed, which will only happen if the ideational superstructure changes in the first place. Institutions refer to markets and other rules, norms and routines that organize and constrain economic behavior at the focal level below. The Western worldview, which underlies all contemporary capitalist societies, is based on individualism, hard-wired work ethic, materialism and rationality with a particular emphasis on “economic rationality”. Economic growth and an ever rising material standard of living appear as one of its most powerful symbols.

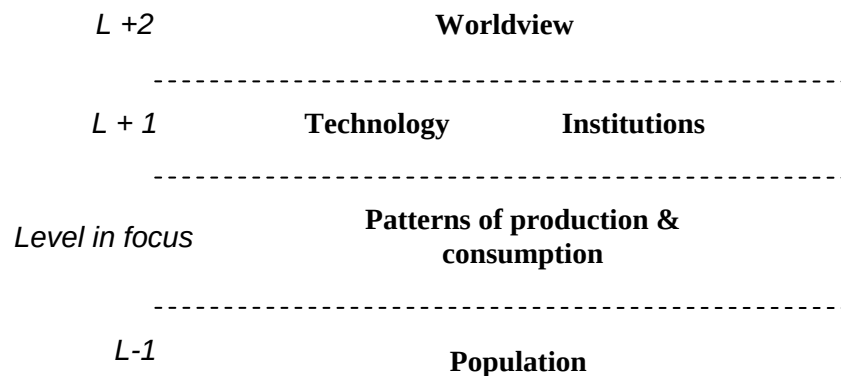


Figure 1. Hierarchical perspective on socioeconomic change

I am advancing here the hypothesis that it is technically possible to impose new constraints on the behavior of agents – firms and households - in order to meet the challenges of oil energy crisis. The institutional changes that will be proposed later in the text lie within the boundaries of the worldview that underlies a capitalist economy.

3. BUSINESS AS USUAL SCENARIO

When dealing with complex systems, like a socioeconomic system, we are forced to apply multiple perspectives if we wish to capture, and even then only partially, its internal workings and dynamics. Building scenarios is one of the tools that help accomplish this task. Several, recently published works offer a variety of scenarios related to peak oil [Holmgren 2009; Rubin 2009; Matutinović 2009, 2011; Robert and Lennert 2010; Friedrichs 2010;]. In the present scenario I assume that peak oil has not occurred yet so that possible changes in the worldview may actively lead major global economies in an adaptive direction to the post-oil civilization. The scenario takes into account two large subsets of the world economy which, anyway, account for most of world energy and resource consumption: The Western group (European Union, United States, Canada and

³ I define worldview as a set of beliefs, symbols, values and segments of objective knowledge that are widely shared in a given society over a considerable period of time (for at least the life-span of one generation).

Japan) on the one side and China and India as fastest growing economies having together more than 2.5 billion population⁴.

Business as usual scenario assumes there is no change in the dominant worldview: two groups put absolute priority on economic growth; consumers in the Western group keep their old habits and preferences while a few hundred of millions of consumers in China and India pursue intensive Western consumption lifestyles. The overall attitude towards energy transition of political leaders and of the majority of voters is best described as “ready to save the world - but not yet”⁵. However, markets agents do perceive that conventional oil is close to being irremediably scarce and they place their bets accordingly. Therefore, the price of oil shows volatility similar to that we experienced in the period 2007-2010, and the world economy flips from expansion to recession on a shortened business cycle. In order to secure enough of relatively cheap energy to fuel economic growth, the US and Canada governments allow off-shore drilling and exploitation of previously protected areas in Alaska, regardless of huge ecological risks and despite protests of environmentalist. In South America, more and more of the protected areas of the Amazon rainforest are rented to Chinese and US companies for oil drilling. Besides pushing out the US companies from some South American oil exporting countries, China continues its oil expansion in Africa and, eventually, takes control of the majority of its oil reserves, at the expense of Western oil companies. Old tensions over the rights to off-shore oil and gas drilling in the South China Sea between China on the one side and other members of Asean and the US on the other, reaches a stage near to an armed conflict. At the same time, the US and Russia enter an open contest for oil exploitation in Arctic. After the failure of military intervention in Iraq and the withdrawal of US forces and its allies, Middle East countries remain largely in control of oil extraction and adapt its dynamics to the current swing in the world business cycle. Their extraction strategy, however, is aimed at preserving enough of oil consumption years for the benefit of their economies and thus they keep the rate of output well behind its maximum potential.

Besides allowing for drilling in environmentally fragile areas, which temporarily drives down oil price and increases overall supply to the world market, governments in both groups increase the subsidies to oil industry and especially so in times of recession in order to stimulate transport industry and personal consumption. In the absence of steady and reasonably high oil price, consumers and industry are confused. Industry does not have a stable horizon for investment in new products and technologies that would go beyond dependency of oil. Consumers hesitate to change their long-established habits and, consequently, their demand does not stimulate industry for a major change in its output.

Driven by West's unhampered demand for consumer goods, China becomes world's major economy in terms of throughput. The accumulation of economic wealth, directly and indirectly controlled by its undemocratic government, has been partially used to build a military power that makes it second only to the US. India does not manage to impose itself as a political or military force in the global contest for oil. However, its economic growth and increasingly Westernized life-styles contribute significantly to global demand of oil. On the other hand, its addiction to fossil fuels makes this overpopulated and ethnically diverse economy politically extremely vulnerable on peak-oil crisis.

Eventually, the world economy faces the change in boundary conditions where it is no longer possible to increase oil production from neither conventional nor unconventional sources. In fact, the use of unconventional oil to keep the price of oil relatively low (in the range of 70-150 \$/bbl) has already depleted the best part of this, “auxiliary” or “second choice reserve”. Therefore, the shape of the world oil extraction looks very similar to that

⁴ Both groups count about 3.5 billion people, or nearly 50% of the current estimate of the world population of 6.8 billion.

⁵ This is the title of the comment in Financial Times after the failure of climate talks in Copenhagen [Crooks, 2010].

of the Hubbert's curve: relatively sharp peak and a steep decline. Faced with changed boundary conditions, the dominant worldview in both groups of countries necessarily changes, but there is no longer time for a well-thought and gradual adaptation of capitalist institutions to new circumstances. Technologies that could have helped the energy transition period have not been developed yet or are only in its early stages. In the meanwhile, major world economic and military powers have reached a high level of political tensions - a result of years of competition for control over the remaining oil fields. The world enters a rapid process of de-globalization and economic depression. High energy prices coupled with the loss of their export markets in the West triggers deep political crisis in China and in India. Disturbingly enough, Western democracies find themselves exhausted by recurrent recessions and economic insecurity, which at the times of final oil-crisis opens space for voting extreme political options that promise "fast and fair" solutions. I leave the likely final outcomes of this scenario to the reader's imagination.

4. INSTITUTIONS FOR CHANGE

According to the theory presented in section 3, the business as usual scenario may be avoided if the Western group changes timely its worldview and introduces indispensable changes in the institutional framework. The requisite changes in the dominant view of the world are following: political elites and the population at large would have to recognize and accept that (1) unbounded material growth of our economies is neither possible nor desirable, (2) that conventional oil will soon become increasingly scarce, and that (3) greenhouse emissions cannot be reduced if our economies continue to increase the use of fossil fuels. I assume that under the appropriate institutional constraints markets are able to achieve certain societal goals related to adaptation to post-oil era and reduction of greenhouse gasses. We identify these adaptations in the change of patterns of production and consumption. Some of the basic *societal goals that markets are expected to realize* are:

1. *Structural transformation of the transport sector:*

- Gradual replacement of the extant fleet based on internal combustions engines with vehicles based on electric motors, and accordingly, transformation of the supportive infrastructure (from gasoline stations to battery recharging network).
- Large switch - up to eighty percent of the present state – from individual to mass transport in urban areas, and in those interurban areas which are characterized by high density of population.

2. *General reduction of greenhouse gasses* in manufacturing, in the electricity generation, and in heating, in conformation with politically expressed abatement targets of major greenhouse emitting economies.

3. *Expansion of investments in renewable sources of energy*, especially for generation of electricity.

4. The process of *technological innovations* necessary to support the above mentioned goals.

In order for markets to actively contribute to achievement of these societal goals, the price of energy needs to be high and stable enough to entice long-term investments in industry and to promote behavioral changes on the consumer side. For this to happen, markets are not enough: as we have experienced recently, they can drive briefly the price of oil as high as 150\$/bbl but they cannot prevent huge price volatility, creating thus an erratic environment for decision makers in industry and in households.

4.1. Threshold oil price

What is the oil price range that would induce requisite changes in the patterns of production on consumption? Based on empirical data and expert estimates from the US

market, it appears that the price of crude oil should not be at any time lower than 150\$/barrel, and that policy makers should increase it gradually to 200\$/barrel. Consumer psychologist Kit Yarrow labeled the price of \$5/gallon, the “tipping point” which is expected to trigger major changes in consumer behavior and “re-conceptualize the role of transportation in their lives” [NY Daily News 2008]. Rubin and Tal [2008] expect to see “quantum shift in driving behavior in America” at \$6–\$7 per gallon—a shift that would bring their driving habits closer to that of Europeans. In the period 2000-2008 motor gasoline prices [EIA 2009] followed oil prices [BP 2009] with strong linear dependency ($R^2=0.99$) (see figure 2). Assuming that strong linear relationship would continue in the future, a simple regression analysis shows that oil price need to reach the level of 150\$/barrel in order to support gasoline price in the range of 4.8-5.10\$/gallon, while an oil price of 200\$/barrel is necessary to drive the price of gasoline in the range of 6-7\$/gallon.

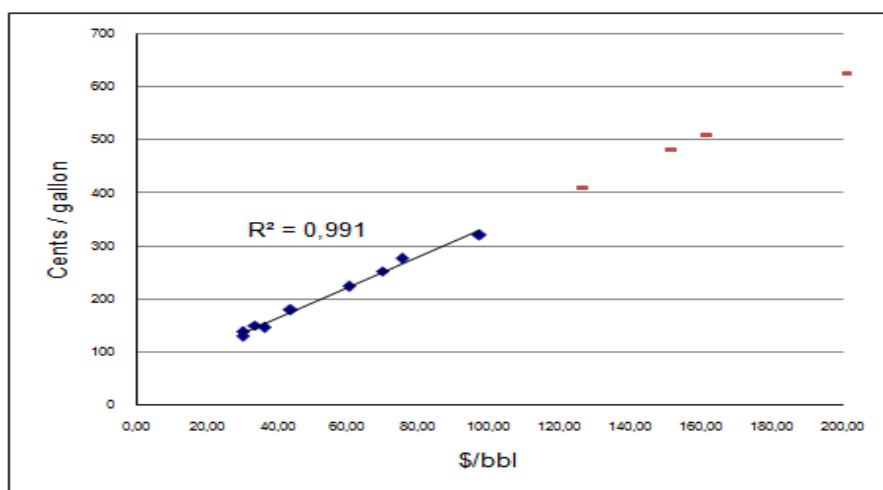


Figure 2. Estimate of oil and gasoline threshold prices

Because consumer’s exact reaction to rising oil prices is contingent to other hard and soft variables like, for example, income, inflation and general attitude towards climate and environmental issues, it not possible to predict accurately the oil price threshold that would trigger a process of irreversible change in habits. However, the above price range can be taken as a reasonable proxy for policy discussion.

4.2. The oil tax and removal of subsidies

Because markets alone cannot stabilize the price of oil in the required range, political decision makers in oil importing countries should consider introducing a new institutional constraint – that of import oil tax – a measure that already have been proposed for the US [Lee 2006; 2009]. Why to tax oil instead of gasoline? By taxing oil policymakers can achieve contemporarily three systemically interrelated goals with the same fiscal instrument: (1) increase the price of gasoline and other oil derivates to induce major changes in the transportation sector; (2) push up prices of coal and natural gas, with the goal to increase the price of electrical energy and thus stimulate energy efficiency and conservation at all consumption levels in the economy. Raising the overall price level of fossil fuels is indispensable if we want to stimulate industry and households to reduce greenhouse emissions – the third policy goal. Increasing the price of electricity and thus reducing the overall demand for energy is absolutely necessary because renewable sources of energy – solar, wind geothermal and biomass cannot be increased enough to meet our current levels of demand (for details see McKay [2008], Smil [2006], Spangenberg and Settle [2009]). The proposition (2) is based on the empirically grounded assumption that prices of coal and gas in the importing countries will closely follow that of oil. If this assumption would not materialize for whatever reason, there is still room for

introducing carbon taxes and cap and trade schemes to help achieve the third goal. Policy makers have on their disposal yet another and complementary institutional instrument - the removal of subsidies to oil industry and to fossil fuels-based electricity generation with the aim of making the real cost of energy transparent to the markets [Hubbard 1991; Templet 2001; Hall et al 2003].

Oil taxes and elimination of subsidies have the main goal of keeping the energy prices high and relatively stable. This also means that import taxes may be temporarily reduced or entirely removed and subsidies extended temporarily back to the industry or consumers if oil prices on the world market would rise abruptly and sharply over the established price range. This measure is necessary in order to secure a degree macroeconomic stability, which is necessary for adaptive processes to take momentum in the economy. The appropriate timing for introducing the oil tax and start removing subsidies to the oil industry is as soon as the world economy returns firmly back to the growth path, which may be as soon as in 2011⁶.

It is almost certain that once the threshold price range has been reached, the global economy would undergo a long recession and enter a de-globalization process [Rubin 2009]. This would pose yet another serious challenge to capitalist democracies and hopefully trigger a cascade of innovative institutional solutions [Matutinović 2011].

4.3. Does it clash with the worldview?

Would these measures clash with the prevailing values and beliefs in the Western societies - those that implicitly or explicitly affect our choices related to energy issues? We can tentatively try to answer this question on the example of the US society, by examining societal attitudes recorded in nationally representative opinion polls of adult population conducted in 2007 and in 2008 [PollingReport 2010], before the onset of recession. One of the most important findings is that population was in the process of accepting the new environment of high and rising energy prices as a permanent condition: in the 2008 poll, 89% of respondents declared to expect that the price of gasoline will go up⁷, while 78% of them thought that the current rise in gas prices represents a more permanent change in prices instead of a fluctuation⁸. Under such expectations of (stably high) future price levels commuters started switching to public transport or using carpooling, they significantly reduced their purchases of large fuel-inefficient cars like SUV's and traveled 4.4% less miles [NYT 2008; White 2008; PollingReport 2010⁹]. Moreover, in 2008 the majority of adult population (61%) supported *more conservation by consumers* of existing energy supplies while 29% of them emphasized more production and 5% both equally¹⁰.

However, when confronted with the possibility of increasing federal taxes on gasoline in order to support energy independence and reduction of greenhouse gases, respondents expressed considerable resistance: 83% of them opposed increasing the federal tax on gasoline in order to reduce the country's dependence on foreign oil and make the United States more energy independent¹¹. Similarly, in a poll conducted in 2007, somewhat lower proportion -58% of respondents - opposed an increased federal tax on gasoline in order to cut down on energy consumption and reduce global-warming (38% was in favor and 4% unsure)¹². On the other hand, when paying higher energy prices was

⁶ As Hirsch [2005; 2007] argued, the time needed for economy to adjust to the new boundary conditions is at least two decades and "effective mitigation means taking decisive action well before the problem is obvious". As I argued elsewhere [Matutinović 2009], during the last price spike the oil market sent a sign that the time is ripe for starting a policy that would stimulate early adaptation and mitigation processes.

⁷ CBS News Poll. May 30-June 3, 2008. N=1,038 adults nationwide. MoE $\pm$ 4. [PollingReport 2010]

⁸ USA Today/Gallup Poll. May 2-4, 2008. N=1,017 adults nationwide. MoE $\pm$ 3. [PollingReport 2010]

⁹ CNN/Opinion Research Corporation Poll. June 4-5, 2008. N=1,035 adults nationwide [PollingReport 2010].

¹⁰ Gallup Poll. March 6-9, 2008. N=1,012 adults nationwide. MoE $\pm$ 3. [PollingReport 2010].

¹¹ FOX News/Opinion Dynamics Poll. June 17-18, 2008. N=900 registered voters nationwide, Moe $\pm$ 3 [PollingReport 2010].

¹² CBS News/New York Times Poll. April 20-24, 2007. N=1,052 adults nationwide. MoE $\pm$ 3. [PollingReport 2010].

placed in a different context, respondents made their choices differently and their support increased: 64% of them declared to be willing to pay higher taxes on gasoline and other fuels if the money was used for research into renewable sources like solar and wind energy (33% opposed; 3% unsure), while 75% would be willing to pay more for electricity if it were generated by renewable sources like solar or wind energy, in order to help reduce global warming (25% opposed; 5% unsure). In the midst of the worst post-II WW recession, public support turned to stimulating growth at the expense of environmental protection¹³. However, recent polls suggest that respondents would again give the priority to environment even if this would mean limiting the amount of fossil fuels supplies or risk curbing economic growth¹⁴.

We can tentatively conclude that adult population in the US is not likely to support higher gasoline taxes, which they may perceive as endangering their established habits of movement and when they believe that tax revenues would be used by the state for rather unspecified goals (energy security and overall reduction of energy consumption). On the other hand, when higher energy prices are perceived to *fund research into renewable sources and generation of electrical energy from renewable resources*, it appears that majority of the population may support new energy taxes. Although far from being conclusive, this tentative insight into consumer attitudes and their likely behavior does not reject the idea of introducing an oil tax as an unfeasible proposal. Moreover, it appears that this instrument may be more acceptable for consumers than rising gasoline taxes directly. An appropriate communication strategy and transparent allocation of tax revenues are, however, crucial for the success of this policy.

5. CONCLUSIONS

Capitalism is the prevailing socioeconomic system in the world today and all of the capitalist countries except China are parliamentary democracies. Therefore, for the energy transition and climate change issues we are primarily looking for solutions that lie within cultural and institutional framework of capitalist democracies. Only in an environment of high and relatively stable prices of energy can our societies hope to achieve requisite changes in production and consumption patterns that may lead both to energy transition and to reduction of greenhouse emissions. According to empirical data and informed guesses by experts, it appears that the price of oil should be in the range of 150-200 \$/bbl in order to trigger long-range changes in industry, technology, and consumer behavior. The institution of market is not able to cope with energy and climate problems by itself. If it is to contribute to the adaptation and mitigation processes of energy transition, a society have to impose new institutional constraints on its workings. We identified these new constraints in the import tax on oil and in the removal of subsidies extended to oil industry and to fossil fuels-based electricity generation. If carefully planned, this measure might be accepted by the majority of the population in the advanced Western countries.

ACKNOWLEDGEMENTS

The author wants to thank the GfK Group for supporting his research work.

¹³ Marist College Poll. April 1-3, 2009. N=1,118 adults nationwide. MoE $\pm$ 3; CBS News/New York Times Poll. Dec. 4-8, 2009. N=1,031 adults nationwide. MoE $\pm$ 3; [PollingReport 2010].

¹⁴ USA Today/Gallup Poll. May 24-25, 2010. N=1,049 adults nationwide. MoE $\pm$ 4; Pew Research/National Journal Congressional Connection Poll. June 10-13, 2010. N=1,010 adults nationwide. MoE $\pm$ 4 [PollingReport 2010].

REFERENCES

- Aleklett, K. / Hook, M. / Jakobsson, K. / Lardelli, M. / Snowden, S. / Soderbergh, B., 2010. "The Peak of the Oil Age? Analyzing the world oil production Reference Scenario in World Energy Outlook 2008", *Energy Policy*, 38 (3): 1398-1414.
- British Petrol, *BP Statistical Review of World Energy* June 2009, <http://www.bp.com/statisticalreview>
- CERA - Cambridge Energy Research Associates, 2006. *Why the Peak Oil Theory Falls Down—Myths, Legends, and the Future of Oil Resources*. www.cera.ecnext.com.
- Crooks, Ed 2010. "Ready to save the world – but not yet". *Financial Times*, January 15, 2010.
- Deffeyes, K., 2005. *Hubbert's Peak: The Impending World Oil Shortage*. Princeton
- Energy Information Administration (EIA) 2010: *Weekly U.S. Regular Conventional Retail Gasoline Prices*. <http://www.eia.doe.gov/>
- Hall, Charles, Tharakan, Pradeep, Hallock, John, Cleveland, Cutler, Jefferson, Michael, 2003. "Hydrocarbons and the evolution of human culture". *Nature* 426, 318–322.
- Hirsch, R.L., 2005. "The inevitable peaking of world oil production". *The Atlantic Council Bulletin* XVI (3), 1–9.
- Hirsch, R.L., Bezdek, R., and Wendling, R., 2005. *Peaking of world oil production: impacts, mitigation, and risk management*. DOE NETL (February).
- Holmgren, D. 2009. *Future Scenarios: How Communities Can Adapt to Peak Oil and Climate Change*, Chelsea Green Publishing, Vermont.
- Hubbard, H. M. 1991. "The Real Cost of Energy", *Scientific American*, Vol. 264, No. 4: 18-23.
- International Energy Agency (IEA), *World Energy Outlook 2009 Fact Sheet*, (2009), Available at: www.iea.org/weo/docs/weo2009/fact_sheets_WEO_2009.pdf
- Jörg, Friedrich, 2010. "Global energy crunch: How different parts of the world would react to a peak oil scenario". *Energy Policy* 38:4562-4569.
- Lee, Henry 2009. "Oil Security and the Transportation Sector." Chap. 4 in *Acting in Time on Energy Policy*. Washington, D.C.: Brookings Institution Press.
- Lee, Henry 2006. "Tame Oil's Wild Price Ride with a Tax." *Christian Science Monitor*, April 13.
- MacKay, David 2008. *Sustainable Energy – without the hot air*, UIT Cambridge, Available at: www.withouthotair.com.
- Matutinović, I. 2007. "An Institutional Approach to Sustainability: a Historical Interplay of Worldviews, Institutions and Technology". *Journal of Economic Issues*, Vol. XLI, No.4, 1109-1137.
- Matutinović, I. 2007b. "Worldviews, Institutions and Sustainability: An Introduction to a Coevolutionary Perspective". *International Journal of Sustainable Development & World Ecology*, Vol. 14:92-102.
- Matutinović, I. 2009. "Oil and the Political Economy of Energy", *Energy Policy* 37: 4251–4258.
- Matutinović, I. 2009b. "Economic Globalization and its Constraints". In Eds. Harold V. Baines and James R. Ursah, *Globalization: Understanding, Management and Effect*. New York: Nova Science Publishers.
- Matutinović, I. 2011. "Oil at 150\$ - the tipping point for changing course?" *Futures*, Special Issue on "Energy Futures", to appear in 2011.
- Nashawi, Ibrahim S., Adel Malallah, and Mohammed Al-Bisharah, 2010. "Forecasting World Crude Oil Production Using Multicyclic Hubbert Model". *Energy Fuels*, 24, 1788–1800: DOI:10.1021/ef901240p.
- New York Daily News, *High gas prices alter consumer behavior*. July 24, 2008. www.nydailynews.com/lifestyle. (Accessed on 11.12.2009.).
- OECD/IEA, 2008. *World Energy Outlook: Edition 2008* (Executive Summary), OECD/IEA, Internet edition: www.iea.org/weo/2008.asp.
- Owen, Nick, A., Oliver R. Inderwildi, David A. King, 2010. "The status of conventional world oil reserves - Hype or cause for concern?" *Energy Policy* doi:10.1016/j.enpol.2010.02.026 .
- Polling Report, 2010. www.pollingreport.com/energy.htm, *Polling Report*, Inc 2010, Accessed April 3, 2010 and on September 9, 2010.
- Robert, Jacques and Moritz Lennert, 2010. Two scenarios for Europe: "Europe confronted with high energy prices" or "Europe after oil peaking", *Futures*, doi:10.1016/j.futures.2010.04.015
- Rubin, Jeff, 2009. *Why Your World Is About to Get a Whole Lot Smaller: Oil and the End of Globalization*. New York: Random House.

- Rubin, J. and Tal, B., 2008. *Getting Off the Road: Adjusting to \$7 per Gallon Gas in America*. StrategEcon—June 26, 4–8, CIBC World Markets.
http://research.cibcwm.com/economic_public/download/.
- Salthe, S. N. 1985. *Evolving Hierarchical Systems*. New York: Columbia University Press .
- Salthe, S.N., 1993. *Development and Evolution: Complexity and Change in Biology*. MIT Press.
- Smil, V. 2006. *21st century energy: Some sobering thoughts*, OECD Observer no. 258/259, December 2006, www.oecdobserver.or, Accessed on 16.2.2010.
- Spangenberg J. H. and J. Settle, "Neither Climate Protection nor Energy Security: Biofuels for Biofools?", *International Relations*, (Ankara) Vol.5, No. 20 (2009) 80-108.
- The New York Times, 2008. *Gas Prices Send Surge of Riders to Mass Transit*. May 10, 2008.
- University Press, New Jersey.
- White, J. B. *American Drive Less, Creating a Problem*, The Wall Street Journal, November 24, 2008.
- Witze, A. 2007. «That's oil, folks». *Nature* 445, 14–17.
- Zittel, W., Schindler, J., 2007. *Crude oil: the Supply Outlook*. Report to the Energy Watch Group. EWG—Series No. 3/2007. October.

PROSPECTIVE LIFE-CYCLE UNCERTAINTIES OF EMERGING ENERGY TECHNOLOGIES

*István Krómer**

VEIKI Institute for Electric Power Research, Budapest, Hungary

ABSTRACT

Reducing the flow of greenhouse gas emissions to stabilize the stock of greenhouse gases, especially in the context of an expanding global economy, require substantial changes in global energy technology mix. Future technology change will come in form of technologies expected to mature in the near or distant future and technologies not yet known.

Endogenous technological change has been introduced in strategic energy analysis since about the mid 1990s by implementing so-called energy technology learning rates, which specify the quantitative relationship between the cumulative experience of a given technology and the cost reductions. Emerging technologies typically evolve through several stages of development. A topical question is how technologies pass from one stage of development to another. The possible changes in the cost trends of emerging technologies can be assessed by different but complementary approaches.

In this report, basing on recent empirical data the long time perspectives of emerging energy technology progress will be scrutinized. An analysis of the technical factors was carried out to identify future barriers that can lead to discontinuities in the slope of experience curves. A comparative analysis was presented at different stages of development including a range of contributing parameters to the learning rate changes. The role of underlying industry characteristics was outlined as well. The cross analysis of the major sources of historical cost reductions for more mature technologies also provides insights to the future cost reduction opportunities.

1. INTRODUCTION

Transition from the conventional energy systems used today to one powered by sustainable energy sources is driven by large scale changes such as rapidly increasing energy demands of developing nations, shrinking fossil fuel reserves, concerns over the impact of carbon emissions on global climate change, which could have staggering impacts on the global economy if transition to a secure energy supply is not realized.

The development of the energy infrastructure in use today had its beginnings in the 19th century. Its development can be described as an evolutionary process not as a designed system project. With the exemption of nuclear fission and hydro power, the energy system of the twentieth century relied upon the combustion of fossil fuels: initially coal and oil and now increasingly natural gas. Planning of the future energy supply mix must be based on the current state and prospects of technology options. The promise of the future technological progress can allow us to envisage energy systems that are capable of realizing climate change mitigation goals. The improved and new technologies will enable:

- to use energy more efficiently, thereby reducing energy consumption and GHG emissions,
- utilize alternative energy carriers that emit less GHG per unit of the final product,
- using systems engineering principles to create alternative means of meeting needs in ways that are less GHG intensive.

* E-mail: i.kromer@veiki.hu; Phone: (+36-1) 457-8273

This report presents likely progress paths of a couple of energy technologies in different phases of their life cycle considered to be able to tackle the long term challenges. The technologies range from more mature to much less developed options.

Two types of technology performance metrics were investigated:

- future energy technologies potential.
- cost improvement potential.

Energy supply models now use experience curves to endogenate improvements in technology. In the planning and forecasting applications emphasis has shifted away from learning curves based on employee productivity and plant-level analysis, toward experience curves aggregating industries and including all cost components. Despite many shortcomings, a simple experience curve using price data alone can be an effective estimator of future prices for technologies during their growth phases in a competitive international market [Alberth, 2008].

The most commonly used single-factor experience curve describes how unit cost decline with cumulative production. While the use of experience curves should not be seen as a deterministic theory of technological learning, the trend has been observed across many technologies and can provide insight into the future cost perspectives. However, transferring experience curve analyses of historical data to prospective studies must be made very carefully. For the purpose of estimating technology learning rates, a proper level of data aggregation has to be choiced. As this report aims to study global patterns of technology changes, we strive to use aggregate global level data.

The electricity supply system has a pivotal role to play in ensuring environmental and social sustainability of future economic and energy systems due to the size of its contribution to the GHG emissions. Hardly any other sector has such a wide range of emerging and prospective technologies promising to transform the conventional energy systems. It is therefore important to survey the developing electricity technologies and to asses their future development potential. The full picture of technological change should not only consider experience curves for specific technologies but also the effects of spill-over in a cluster of related technologies. For example technologies which utilise CO₂ capture and sequestration in some form will also have many common plant components and will experience spill-over benefits from increasing experience pertaining to any other plant type.

2. TECHNOLOGY DEVELOPMENT LIFE-CYCLE

Technology development is conceptualized as a gradual process that involves different stages of progress. There is an ample evidence from the literature that energy technologies have distinct stages of development that correlate to different learning rates. A way to improve the prediction possibilities of experience curve could be to include more information on the stage of development of a specific technology. The future energy technologies exhibit different stage of development and maturity. Several authors identified three phases of development (radical, incremental and mature), others place the technologies in four categories (emerging, evolving, mature and reviving). The distinction between the two classification is in the identification of the reinvigoration phase.

Emerging technologies have existed for a relatively short time and have almost, no market share, and may never reach any significant commercialization. In the light of existing low levels of installed capacity and presence of market constraints, the emerging technologies are likely to have significant potential for cost improvement. However, for several advanced and complex technologies early cost estimates based on laboratory-scale projects and pilot plans were typically lower than the costs subsequently realized for the early commercial plants. Thus the costs often increase rather than decrease in the early phase of commercial deployment. The liberalisation of the industry has increased the dependence of the emerging technologies on public R & D and promotion schemes.

Incremental / evolving technologies have niche market commercialization and have potential for significant cost reduction. Evolving technologies have faced some market constraints, that limited their growth. Their moderate or low levels of installed capacity suggests that this technologies still possess scope for significant capacity increases and cost reductions. Incremental development exploits existing technology, focus on cost or feature improvements, improves competitiveness within current markets or industries.

Technologies in the mature category have been developed and utilized over a long period of time and have had a major share of the expansion of the energy industry worldwide. These technologies due to their mainstream position and widespread use, have found few market constraints. Mature technologies generally have saturated the market, have well known characteristics and have limited potential for cost reductions. Given the high levels of existing capacity for established technologies, a doubling of capacity and further cost improvements can only take place over a long period of time.

Reviving technologies have been utilised for a long time. The existing high levels of installed capacity for these technologies suggest that they have limited capacity for cost reductions. Besides purely technological developments, myriad factors such as market competition, changes in industry structure, fuel prices and regulations related to health, safety and environment affects the reinvigoration of mature technologies.

A topical question is how technologies pass from one stage of development to another. The possible changes in cost trends of developing technologies can be assessed by different approaches. As installed capacity increases, eventually an emerging technology can become evolutionary and an evolutionary plant can become a conventional one. Therefore, there must be some point defined when technologies are assumed to pass from one vintage to another.

The inflections between vintages are called breakpoints [Gumerman, 2004]. According to this reference, a revolutionary technology is redefined as an evolutionary technology after three doublings of capacity, and an evolutionary technology is redefined as a conventional technology after five doublings of capacity. Potentially, even a revolutionary technology could become conventional after eight capacity doublings.

However, rather than being a simple linear process, the different stages of technological development are highly interactive. Each stage of development process requires different types of incentives to promote the overall goal of technology change.

3. DEVELOPMENT OF LOW- OR NO-CARBON ENERGY TECHNOLOGIES

3.1. Photovoltaics

The cost of photovoltaics (PV) has decreased by a factor of nearly 100 since the early 1950s. Markets for PV are expanding rapidly, recently growing at over 40% per year. However, PV does not compete economically with conventional sources, such as coal and gas, or even with leading renewable sources such as wind and biomass. PV in the evolving phase remains a niche electricity source.

In a 26-year long period from nascent commercialization (1975-2001.) there was a factor of 20 reduction in the cost of PV modules. Crystalline silicon PV comprised over 90% of production over this period and its share increased in the second half of the period [Nemet, 2006]. In explaining cost declines in this time period plant size and cell efficiency were the most important contributors to cost reduction, cost of silicon was moderately important and other factors (e.g. wafer size, poly-crystalline share etc.) were of minor importance. The importance of economies of scale fits with other studies [Coulomb, 2006]. According to expert assessments the share of material price in the total cost of the module is likely to grow in the upcoming years.

Supposing that the two most important sources of the cost reduction remain the scale and efficiency improvements in the future, the single extension of the historical learning rate and using an 11% annual growth assumption would deliver 1USD/W modules in about 2030 and 0.10 USD/W modules in about 2090. There are claims that 1USD/W modules would be too expensive once PV accounts for more than 5-10% of total electricity generation. It is very difficult to predict which of the more innovative developing technologies will break through and when this breakthrough will occur and how its experience curve will look like. Producing electricity on this basis is among the most expensive GHG abatement options. PV should nevertheless be included in long-term energy scenarios.

3.2. Wind turbines

Wind energy has historically been used to support human activities. Since 1980s wind turbines are considered an important technology mitigating GHG emission, as wind energy is considered clean and safe. Since the early 2000s off-shore wind turbines have been developed and installed. Harnessing wind energy through on-shore and off-shore wind farms has been one of the fastest growing forms of renewable energy in the past decade. Currently, installed world capacity is in the range of 100GW and second only to hydropower as a source of renewable electricity.

Some 60% of cost reductions in the last two decades are estimated to be the result of economies of scale brought about by increased market volume. The remaining 40% of cost reductions can be attributed to technology improvements. However, analyses point out that it appears to be almost impossible to distinguish between reductions due to technological learning and those due to scale effects. The cost reductions presented in different studies varies considerable. Using a large number of price observations, the authors of [Coulomb, 2006.] estimated that the costs for wind turbines have fallen by 12.7% with every doubling of installed capacity.

Technology development and further experience will reduce cost of both on-shore and off-shore wind turbines. As historical cost reductions can be described as a result of incremental technology improvements, the future cost reductions are likely also to rely on incremental improvements. Based on the past experience of incremental improvements, a cost reduction of 10% per every doubling of the installed capacity can be suggested for on-shore as well as off- shore wind turbines.

3.3. Bioenergy systems

The bioenergy studies reveal large differences to estimate empirical experience curves for investment costs of biomass fuelled power plants. The reason are the varying plant costs due to differences in scale, fuel type, plant lay out, region etc. The cost of bioenergy will depend on both the bioenergy feedstock and on the conversion technologies. The biomass systems are complex and comprise many types of combinations of conversion technologies and supply chains. Smaller cost reductions will be expected for well established, mature technologies and larger cost reductions may be achievable for new innovative technologies. For large fluidized bed boiler plants, the total plant costs have fallen by 7-10% with every doubling of installed capacity [Junginger, et al. 2005.]. The experience curve approach seems to be more efficient when production costs of the final energy carrier are analyzed. Electricity from biofuelled CHP plants yields an 8-9% reduction of electricity production costs with each cumulative doubling of electricity production. Compared to other technologies- such as wind power or solar PV- significant learning by doing occurs during plant operation and maintenance. For conversion technologies a 5% cost reduction can be estimated for every doublings of installed capacity. This assumption is based on the experience gained with advanced fossil fuel technologies.

3.4. Natural gas combined cycle power plants

Natural gas combined cycle power plants (NGCC) feature the best efficiency of all thermal based electricity generation technologies applied nowadays. The efficiency is mainly governed by the efficiency of the gas turbine turbo set. The 60% efficiency barrier can be reached in the near future. However in the long run of the future development the efficiency of natural gas combined cycle power plants will not exceed the 65% barrier. As to the costs of installed capacity gas turbines are the most cost-effective technology for electricity generation. This was not the case four decades ago. The technology could be characterized as precommercial until the early 1960s, the costs were high. After about 1963 the improvement rate has an average value of 22% per every doubling of the installed capacity. Later in the time period of 1975-1993 the improvement rate declined and it has an average value of 13% per every doubling [Jamashb, 2007.]. The specific investment costs are anticipated to further decline with a learning rate around 5% as higher unit capacity gas turbines are assumed. However, the decline of the specific investment costs is likely level off in long run. Thus, NGCC technology is likely to remain the benchmark technology for some years to come.

3.5. Pulverized coal-fired power plants

Among various fossil fuels, coal is abundant and widely reserved throughout the world, it is one of the most important energy sources.

Pulverized coal-fired power plants have undergone significant technological change over the past century, and are expected to be an important part of future power generation portfolios. Technology improvements in pulverized coal boilers along with other plant components have yielded significant economies of scale and efficiency gains, reliability and environmental performance of the overall power plant. When only the best commercially viable plants were considered, a study found sustained improvements in the overall thermal efficiency of PC plants over 1940-2005 with an average rate of improvement of 3.8% for every doubling of cumulative worldwide capacity [Yeh, 2007.]. If this trend continues, the projected thermal efficiency of commercial PC plants may reach 46.4% when the estimated worldwide installed coal-fired capacity reach the level of 2000 GW, which is estimated at 2030 [EIA, 2010]. Climate policies and regulatory actions could accelerate the efficiency improvements.

For new PC boilers, the capital cost reduction for every doubling of installed capacity averaged 5.6% over the period of (1942-1999).

3.6. CO₂ Capture and Sequestration

In 2007 the global electricity demand was 18.783 TWh of which 2/3 was generated by fossil fuels. Despite the growing climate change concern, the electricity demand will increase and a major part of the electricity will be generated by fossil-fuelled technologies.

CO₂ capture and sequestration technology (CCS) is an important new class of environmental technology with the potential to allow continued use of fossil fuels without significant GHG emissions. CCS is a technology that has the potential to yield dramatic reductions in CO₂ emissions from fossil fuel use by capturing the CO₂ that is currently released to the atmosphere. An important feature of the CCS technologies are thermodynamic efficiencies, which are approximately 10% less than generation technologies without carbon capture and sequestration. Integration of CO₂ capture, transport and geologic sequestration has been demonstrated in several industrial applications.

Recent studies of CO₂ capture and storage for power plants have focused on currently available technology. Reliance on cost estimates for current technology has the disadvantage of not taking into account the potential for improvements that can affect the overall role of CCS as a climate change mitigation strategy and the long-term

competitiveness of CO₂ capture systems in different applications. However, widespread CCS deployment will not occur without a sufficiently strong climate policy driver. Thus, changes in CCS costs over time depend on the policy scenario and its influence on total installed CCs capacity in competition with other carbon mitigation options. In a preliminary modeling study an average learning rate of 12% was used to model the expected rate of capital cost decline for CCS systems in the long run [Riahi, et al. 2004.].

4. FUTURE ENERGY TECHNOLOGY MIX

Future energy technology mix can be the response to the long term challenges facing the humanity:

- tackling climate change by reducing carbon dioxide emissions.
- ensuring secure clean and affordable energy supply in face of growing energy needs.

Each technology examined in this study has its own set of characteristics that are valued to more or lesser extents depending on the contextual issues. Research results show that fundamentally different future energy system structure might be developed with similar overall costs [Gritswskyi, 2000.].

According to this recent energy–systems engineering study, the endogenous technology learning with its uncertainty and spillover effects will have the greatest impact on the emerging energy system structures during the first few decades of the twenty–first century. However, fundamental changes in global energy systems tend to occur slowly. The new technologies can take over the market gradually. The share of the market controlled by a new technology plotted against time follow an S-shaped function. In the beginning risk averse firms hesitate to use the new technology. The diffusion rate increases over time as uncertainty is reduced. A change in costs over time also accelerates the spread of new technologies. Long lived capital in the old technology may only be replaced with a new technology as the old physically depreciates. Thus, the transitional process from the first feasible prototype to the technology diffusion takes time.

Owing to the uncertainty in experience curves, the optimal solution becomes less certain. As a result, there is a broader investment portfolio of technologies with slower diffusion of any particular technology.

Concerning the future fuel mix, energy outlooks tend to agree that the contribution of renewable energy source will increase but not dominate the electricity generation sector in the next decades.

According to a recent projection of the world total electricity generation, conventional fossil-fired technologies, which are primarily coal-based, predominate other forms of generation accounting for 64.5% of total production in 2035 [EIA, 2010.]. Limited penetration of wind and solar (4%) with 2.5 and 3 doublings of installed capacity reflects the fact that they are imperfect substitutes for electricity from other generation sources. They are intermittent, and could only penetrate further with investments in storage, redundant capacity or through use of reliable back- up technology. The biomass share in power generation can reach the same level as well.

Table 1. LEARNING RATES OF ENERGY TECHNOLOGIES

Technology	Period	Classification	Cost reduction/capacity doubling (%)	Reference
PC boilers	1942-1999	Reviving	5,6	7
NGCC	1950-1963	Emerging	n.a.	6
NGCC	1963-1980	Evolving	22	6
NGCC	1975-1993	Mature	13	6
Wind	1991-2003	Evolving	12,7	4
PV	1975-2001	Evolving	23	3

Biomass cofiring	1980-1995	Evolving	15	5
Biomass cofiring	1995-	Mature	7-10	5
CCS	2001-	Emerging	12	9

CONCLUSIONS

A critical factor governing future anthropogenic emissions is the rate and magnitude of technological change toward low- or no-carbon technologies. Any successful strategy to significantly reduce GHG emissions will require actions not only to deploy low-emissions technologies that are available now, but also to foster innovations on new technologies, many of which have not yet been invented, commercially developed or adopted at a significant commercial scale. A wide range of technologies from more mature to much less developed technologies could reduce GHG emissions. A fundamental lesson learned from the experience curve studies is that low carbon technologies are more costly than the conventional technologies, but the costs of formers can be assumed to decrease with increases of their market share so that at a given moment they will be more attractive choice than the old technology, which is more mature and experiences less cost reduction. The results of the study indicate that there are significant prospects for accelerated development for a range of low-carbon technologies, including wind power, solar PV. However the pace of acceleration differs across the technology mix due to the different stages of development (Table 1.).

The uncertainty of long-term technology projections can be reduced by a combination of experience curve analysis and judgemental methodologies, such as interviewing experts, expert panels, etc.

REFERENCES

- Alberth, S.: "Forecasting technology costs via experience curve- Myth or magic?" Elsevier *Technological Forecasting and Social Change* 75 (2008) p. 952-983.
- Coulomb, L. Neuhoﬀ, K.: "Learning curves and changing product attributes: the case of wind turbines". EPRG Working Paper, 2006, 07/30.
- EIA: *Reference Case Projections for Electricity Capacity and Generation by Fuel*. US Energy Information Administration, International Energy Outlook 2010.
- Gritsevskiy, N. Nakicenovic: "Modeling uncertainty of induced technological change". *Energy Policy* Vol. 28, 2000, p.907-921.
- Gumerman, E. Marnay, Ch.: *Learning and cost reductions for generating technologies in the National Energy Modeling System (NEMS)*. 2004, Lawrence Berkeley National Laboratory, LBNL-52559.
- Jamashb, T., Köhler, J.: *Learning curves for energy technology: A critical assessment. Delivering a Low Carbon Electricity System: Technologies, Economics and Policy*, Editors: Grubb, M., Jamashb, T., Pollitt M. G., Cambridge University Press. 2007.
- Junginger, M., Faaij, A., Björheden, R., Turkenburg, W. C.: "Technological learning and cost reductions in woodfuel supply chains in Sweden". *Biomass and Bioenergy*, 2005. 29 (6) pp. 399-418.
- Nemet, G. F.: "Beyond the learning curves: factors influencing cost reductions in photovoltaics". *Energy Policy*, 34(17) 2006. p.3218-3232.
- Riahi, K, Rubin, E. S., Taylor M., Schrattenholzer, L. Hounshell, D.: "Technological learning for carbon capture and sequestration technologies". *J. Energy Economics* 26 (4) (2004) p.539-564.
- Yeh, S., Rubin, S. E.: "A centurial history of technological change and learning curves for pulverized coal-fired utility boilers". Elsevier *Energy* 32 (2007) p. 1996-2005.

OPTIMIZATION PROPOSAL OF THE RES-E SUPPORT MODEL IN PORTUGAL: COMPARISON OF THE PORTUGUESE, SPANISH AND GERMAN MODELS

Sousa, C . & Cabugueira, M.*

*Applied Economics Research Center, Lusófona University, Campo grande,
376, 1749-024 Lisbon, Portugal*

ABSTRACT

Abstract text Evaluating the recent literature and political options on regulatory instruments to promote renewable energies, it seems that the discussion is focusing on two possible solutions: feed-in tariffs (FITs), and green certificates. So far the majority of EU countries, Portugal included, that apply FITs as the central support instrument, displays the best performance in relation to renewable energies development. The results that have been attained in Germany and Spain show how the implementation of suitable FIT models can be reflected in successful electricity generated from renewable energy sources (RES-E) support policy. The German model stands out for its use of degressive tariffs, while the Spanish one is characterized by the feed-in premium option. With the present paper, we seek to contribute to a more efficient and equitable promotion and incorporation of RES-E into the Portuguese electricity market, by discussing a proposal for the optimization of the Portuguese FIT model inspired by its Spanish and German counterparts. The goal is to present an optimization proposal for the actual Portuguese feed-in model that reconciles investors' objectives with long-term sustainable solutions characterized by an increase in the consumer surplus. It must be remembered that the cost of energy is borne by society (enterprises, consumers, taxpayers), which means that it is necessary to bring about that balance in the most efficient way. In order to do this, it should be reached a regulatory solution that guaranties a tradeoff between the benefits to society and the costs of using the available resources, in the light of the transfer costs to society.

Keywords: RES-E, feed-in tariffs, efficiency, effectiveness, equity

1. INTRODUCTION

The large scale use of electricity produced from renewable energy sources (RES-E) has been the subject of support policies motivated by the growing concern over the security of energy supply and environmental sustainability especially when it comes to climate change. In the European context, the debate over the RES-E support systems is included in the discussion over the single energy market recommended by the EU (European Union). This debate has introduced profound regulatory reforms in the member states (MS). The European Commission (EC) holds that the completion of the European Energy Project would be made simpler if the regulatory framework for RES-E promotion could be harmonized. The reduction in existing disparities in negotiation between countries, as well as an increase of transparency in transactions would translate into a more efficient exploitation of resources in all EU countries (EC, 2005).

However, the conditions for this to happen have not yet been met. On the one hand, one must take into account the specificities of each country – different renewable potentials, support policies initiated at different times and national goals; on the other hand, the internal electricity market is still not adequately working. For instance, the interconnection capacity need to be strengthened, the national supports for conventional energy sources continue to create market distortions, and we still do not have sufficient

* Corresponding author; E-mail: sousa.d.catia@gmail.com

experience to decide on the most appropriate support instrument to adopt (EC, 2005 and EC, 2008).

As an alternative to harmonization, the EC suggests that the MS cooperate more closely between themselves with the aim of optimizing their existing support systems. With this recommendation, the EC wishes to hasten the commitment between communitarian goals and national priorities, through a cooperation and convergence solution between countries, gradually expanded throughout the EU, i.e., to implement a bottom-up harmonization.

Currently, the most used central support instruments to RES-E in the EU are feed-in tariffs (FIT) and green certificates. Despite countries that chose FITs display the most efficient and effective performances – as demonstrated by Spain and Germany – the adoption of this instrument does not guarantee the success of the support system. RES-E development depends on the existence of additional parameters which together with the central instrument constitute the support model itself.

This work consists of the construction of an optimization proposal of the Portuguese feed-in model (FIT model), inspired by the Spanish and German models. Our goal is to reach a regulatory solution compatible with the liberalization process within the electricity sector; that it may be efficient and equitable, since RES-E supports carry costs to society (enterprises, consumers, taxpayers). All this must be achieved without compromising the effectiveness of the model, in light of the recommendations of the directive 2001/77/CE and of the Kyoto protocol.

The following chapters will describe the main aspects of the development of the optimization proposal of the national model, namely: we mention the critical design parameters that must be present in all FIT models, carry out a comparative analysis between the Portuguese, Spanish and German support models, and finally present the optimization proposal itself.

2. FEED-IN MODELS: CRITICAL DESIGN PARAMETERS

The promotion of RES-E goes beyond the choice of the central instrument; each country must adopt, keeping in mind individual particularities, a support model that integrates elements that complement and potentiate its action. This fact justifies the multiplicity of models that exist within the EU, including among ME whose main instrument are the FITs.

To build a support system, the regulator has at his disposal a multitude of options, called design parameters, which he pairs with the central instrument, in order to obtain the best performance according to the reality in which it will operate. Regardless of the diversity, all FIT models must have design parameters considered critical, because they are essential for a successful RES-E support policy, namely:

Stepped Tariff – Discriminatory tariff for the same technology, taking into account the associated marginal production costs of RES-E. The tariff level lowers as the efficiency of the production plants increases.

Degressive Tariff – Yearly, the tariff level for new RES-E plants is reduced according to a specific legally pre-established degression rate for each renewable energy, in line with the respective learning curve, which may be built upon national or international indicators.

Feed-in premium – Alternate tariff structure to the fixed tariff. It consists of a specific bonus for each RES, guaranteed for a legally stipulated period, which is paid to RES-E producers that choose to sell their output in the conventional electricity market (for this structure, the purchase ceases to be mandatory). The producer's final remuneration results from the sum of the amount they receive for selling the RES-E in the spot market plus the value of the feed-in premium (Klein et al., 2008).

Price setting methodology – Formulates the remuneration level. It may be based on production costs or avoidable external costs.

Duration of support – Defines the time period for the support.

Purchase obligation – The net operators, the suppliers of electricity or the final consumers are obligated to purchase the produced RES-E.

Tariff adjustment – The tariffs must be adjusted between the revision periods.

Model revision– To ascertain if the overall model stills adequate for the defined energy goals or if it must be the subject of alterations.

Peak generation differentiation – Differentiation in the level of remuneration, according to peak and off-peak periods.

Forecast obligation – The RES-E producers must provide information about the RES-E that they estimate to inject into the network.

Burden sharing – Defines to whom the costs associated to the promotion of RES-E are imputed.

3. COMPARATIVE ANALYSIS

The comparison between the critical design parameters has allowed us to identify the differences between the Portuguese, German and Spanish models. Our choice fell on these countries because: 1. These are the two countries whose RES-E support policies achieved the best performances; 2. Each model has a differentiator parameter that can tell the models apart not only between themselves but also between those models and the design adopted in Portugal; 3. In the context of the Iberian Electricity Market (MIBEL), it makes sense to analyze the Spanish RES-E support policy in an attempt to reach regulatory convergence; 4. Being that it is the UE's goal to bring about a harmonization in support instruments, the comparison exercise between alternative designs currently in use in the EU is additionally relevant.

Table 1. Comparison of critical design parameters of the Portuguese, Spanish and German FIT models.

Parameters	Portugal	Spain	Germany
Stepped Tariffs	Yes (based on location, installed capacity and fuel type)	Yes (based on installed capacity and fuel type)	Yes (based on location, installed capacity, fuel type and output produced)
Degressive Tariffs	No	No	Yes
Tariff structure	Fixed tariff	Fixed tariff or feed-in premium	Fixed tariff
Price setting methodology	Avoidable external costs	Production costs	Production costs
Duration of the support	15 years or until total maximum production fixed by law for every RES is reached	Project durability	20 years
Purchase obligation	Yes	Only for the fixed tariff	Yes
Tariff adjustment	Monthly, depending on the consumer price index (CPI)	Yearly, depending on the CPI. Payment reviewed periodically by the government. In the feed-in premium, total payment has cap and floor limits.	For 20 years the tariff level remains unchanged
FIT model revision	Periodic revision, not legally determined	4 years	4 years
Peak generation differentiation	Yes Only mandatory for hydroelectric plants	Voluntary Option available only for some renewable groups	No
Forecast obligation	No	Yes	No

Burden sharing	Equal for all electricity consumers	Equal for all electricity consumers	Yes, except for electricity intensive industries

According to the information on table 1, we can see that feed-in premiums and degressive tariffs make up the differentiating parameters in the Spanish and German models, respectively. For the determinant function we believe they play in the success of the models, it is pertinent to more fully understand them.

3.1. Feed-in premiums

Feed-in premiums were first introduced in Spain through the Royal Decree (RD) 2818/1998, with the aim of encouraging the gradual participation of RES-E producers in the electricity market, while simultaneously mitigating the risk to investors, by assuring a certain level of support, regardless of the evolution in market prices (González, 2008). This tariff structure reduces market distortions by favoring both demand-oriented RES-E production (superior remuneration for peak demand periods) and competition environment.

With this tariff option, the producers have the opportunity to choose between the fixed tariff and feed-in premium. The decision is valid for one year, at the end of which the producer may choose to change or stick with the tariff structure.

Currently, the RD 661/2007 is in force, whose main introduced modification was a cap and floor system, regarding the total remuneration received by the producer. This system, by reducing the current flexibility in remuneration, may be seen as a retrocession to the previously implemented measures by the Spanish government. However, its implementation allows the government to control the profit made by producers, while at the same time contributing to the stability of the system, with the introduction of a minimum remuneration limit (Klein et al., 2008). There is obvious concern, by the Spanish authorities, with the increase in the income of producers and subsequent charges to final consumers. (González, 2008).

The option of feed-in premiums is not available for every renewable energy type specified by the Spanish legislation, due to the different phases of maturity of the technologies. The b.1.1 subgroup –photovoltaic solar energy – is remunerated exclusively through the FITs. The renewable power plants that belong to group b.3 – geothermal energy, waves, tides, warm and dry rocks, ocean-thermal and marine currents – have reference premiums, but there is no cap and floor for remuneration.

3.2. Degressive tariffs

Degressive tariffs were introduced in Germany in 2000, at a time when the RES-E support model was restructured, resulting in the *Erneuerbare Energien Gesetz* (Renewable energy sources act – EEG). This formed the necessary legal frame for the development of other renewable sources, besides the wind energy (Klessmann et al., 2008).

According to the EEG, the RES-E tariffs suffer an annual reduction according to each technology degression rate pre-defined in legislation, applicable only to the new renewable power plants of that specific year. In this manner, the investors have a tendency to invest sooner, to benefit from higher remunerations, allowing the RES-E goals to be reached quicker, increasing the FIT model effectiveness.

The German model wants to incorporate the cost reduction associated to the learning-curve effect in the RES-E support system. This design parameter functions as an incentive to technological improvements and cost reduction, promoting dynamic efficiency.

The static efficiency is also promoted, as, for a particular RES-E plant, the tariffs fixed by the EEG remain unchanged for 20 years – there is no inflation adjustment – leading to a real tariff reduction. From investor's point, degressive tariffs are more reliable

than periodic adjustments, since they know, beforehand, which degression rate will be applied over the earned remuneration for the support period. This approach ends up by awarding a certain degree of stability while planning the development of new investments – contributing to the increase in effectiveness – while forcing the RES-E prices to go down (KEMA, 2008).

This framing of events instills equity in the FIT model, since degressive tariffs translate into lower costs to consumers without harming the increase in investment in RES-E (Klein et al., 2008). The decreasing on consumer costs is explained by the tariff reduction throughout time to accompany the technological breakthroughs that result from the learning effects.

4. OPTIMIZATION PROPOSAL OF THE PORTUGUESE FIT MODEL

Maintaining the matrix of the FIT model currently in play under de decree-law 225/2007, we propose a convergence of this model with the best practices, identified in the Spanish and German models, emphasizing the design parameters that directly affect the calculation of the final remuneration.

4.1. Tariff formulation

The tariff formulation encompasses the parameters that directly influence the RES-E producer's final remuneration. Much like Spain, the co-existence of two remuneration options assures freedom of decision for producers over which tariff structure they prefer, since the ideal conditions for a competitive environment aren't always present. This is also a good way of maintaining risk in moderate levels.

For both remuneration options, the tariff formulation maintains the price-setting methodology based on avoidable external costs, so as to incorporate the social and environmental RES-E benefits, and also becomes subject to degressive tariffs. In the event of the producer opting for fixed tariffs, the tariff formulation suggested is described by the following equation:

$$R_{Tn} = [R_{Tb} \times (1 - d_T)^{i-b}] \times (1 + CPI_n) \times K \quad \text{Eq. 1}$$

As can be seen, both peak generation differentiation – K – and tariff adjustment in function of CPI, remain.

The proposed FIT formulation means that, like in Spain and Germany, one must determine, through legislation, the absolute tariff values for the year when the optimized model – R_{Tb} - will come into application. However, so as not to harm the transparency of the model, the Portuguese regulator must continue to disclose the calculation formula and attributed values to each variable that gave rise to the fixed values.

The remuneration by feed-in premiums has the following expression:

$$R_{Tn} = M_P + [\sigma_{Ti} \times (1 - d_T)^{i-b}] \times (1 + CPI_n) \quad \text{Eq. 2}$$

Where:

R_{Tn} : Current remuneration by KWh, for each renewable energy source

R_{Tb} : Remuneration fixed legally, in the foundation year of the current legislation, per KWh for each renewable energy source

n: Current year of remuneration

CPI_n : Consumer price index for the year n

K: Peak generation differentiation

M_P : Market price

σ : Additional premium

b: Foundation year of the current legislation

i: Date for the start of RES-E plant operations

T: Technological category
d: Degression rate

In the case of the feed-in premium, the formula for the calculation of the RES-E remuneration becomes dependent on the conventional electricity market price, to which is added a premium is – σ – based on the avoidable external costs and subject to a degression tax specific for each renewable resource.

We also suggest adopting the cap and floor system for remuneration, as a mean of protection against the variability in production costs that the market may have to face, since an increase in costs with RES-E support system is only acceptable when social and environmental benefits arise. The existence of a cap and floor mechanism reduces the investor's exposure to risk by ensuring they receive a minimum remuneration, while protecting consumers by establishing a maximum legal limit for the final remuneration, positively influencing the dynamic and static efficiencies.

The variables to consider while determining reference feed-in premiums and cap and floor values must be adequate to the Portuguese reality, must be compatible with national priorities in renewable energy and must have its values annually adjusted, in line with the inflation rate.

It is to be expected that market integration, through the sale of RES-E in the spot electricity market, will favor the competition and consequently reduce, in time, the costs associated to its promotion. The introduction of feed-in premiums must be adequately structured. Like Mitchell (2008, quoted by Langniß et al., 2009) states, one must choose which technologies fall under a certain remuneratory option, as well as under which conditions. Otherwise, this option is only viable for more mature technologies (e.g. onshore wind energy).

Theoretically, feed-in premiums are the fairest tariff option, since they allow us to eliminate the competitive edge offered by conventional fuels, as long as the premium effectively matches the RES-E's environmental benefits. This would increase the competition and eliminate the need to resort to the imposition of quotas. In practice, given the complexity around the quantification of RES-E benefits, the main goal of the enforcement of feed-in premiums is the introduction of market signals, to make the FIT model more compatible with competitive practices. Taking into account the growing tendency of opting for an integrated market solution, establishing a feed-in premium that can still guarantee sufficient stability to investors, is a major step in that direction.

When it comes to the introduction of degression rates for both tariff structures, the proposed tariff formulation aims, on one hand to endow the Portuguese model with higher dynamic efficiency, encouraging a continuous reduction in production costs through learning, on the other hand promote equity through redistribution of surplus by producers and consumers.

The more recent a renewable plant, the fewer remuneration it receives. Pre-defining degression rates will put further pressure on the market. The goal is to encourage investors to anticipate the construction of renewable plants, and to promote improvements in efficiency and cost-reduction for the new production units. This feed-in variant will allow Portugal to take into consideration technological innovations and learning effects, something that we don't see happening in the current model.

One must keep in mind that degression rates, apart from following the learning curve of each renewable energy type as well as its level of maturity, must consider national specificities. Degression is applied annually both to FITs and to feed-in premiums, but unlike the German model, the tariff subject to the degression rate is also adjusted annually. With this alteration, we aim at making the tariff mechanism more flexible, so that it can more easily adapt to possible alterations that can occur.

Portugal has, thus, the possibility of reducing the risk of a steep increase in producer profitability, and of avoiding excess remuneration being awarded to those facilities that have more financial viability due to continuous cost reduction.

Degressive tariffs will contribute to an increase in the stability and security climate essential for successful investments. The degression rate will focus exclusively on renewable plants to be licensed in the future. Investors will now know more exactly how much they receive per KWh of produced RES-E, which gives them guarantees to plan for future investments, since the financial risks are lower and enjoy lower financing costs.

By including degression tariffs in the support model, Portugal increases the probability of meeting its own RES-E goals, in a shorter time frame – increasing effectiveness – with an improvement of dynamic efficiency and equity.

4.2. Other design parameters

Apart from the parameters implicit or explicitly mentioned in the expressions for tariff formulation, the optimization proposal of the national RES-E support model contemplates the alteration and introduction of other critical design parameters. The remainder, not mentioned here, remain unchanged.

4.2.1. Tariff adjustment

In the proposed model, this parameter continues to exist, both in the fixed FITs as well as in the feed-in premium and respective cap and floor options. The frequency of adjustment becomes annual and remains indexed to the CPI. The change in the adjustment frequency from monthly to annually aims to increase the security and stability of the model.

4.2.2. FIT model revision

In the proposed model, legally pre-established periodic revisions of all parameters come into play. The frequency of revisions is not defined here, since it should be based in technical criteria, with adequate ponderation. Both in Spain and in Germany, revisions take place every four (4) years, but this does not mean that this is the right frequency for Portugal. For now, it is important to understand that revision periods must be spaced out, so as not to disturb the stability of the model; however, they must take place with a frequency that allows one to keep track of RES-E production costs. This parameter will contribute to the stability and safety of the support model, once the investors are to know exactly when the FIT model is revised.

On the other hand, revisions allow for the correction of inefficiencies, i.e., through degression rates modification, cessation of supports when a certain installed capacity goal is reached or even after a certain period of time. Periodic revisions must maintain the profits of producers on moderate levels, for if the remuneration is high, the incentive for producers to reduce production costs will be lower.

4.2.3. Forecast obligation

This parameter allows for a better RES-E integration in the electricity system. In order to make the RES-E support system compatible with a competitive market, the proposed model adds, to peak generation differentiation, the fact that it becomes mandatory to predict RES-E production, including for intermittent RESs or those with high volatility.

Forecast obligation must be introduced gradually, allowing producers time to adapt their production units to this new requirement. The effectiveness of this parameter is only possible if it contemplates the application of penalties, in situations where prediction deviations are higher than a previously to-be determined legal level. In this sense, this parameter will act as a reinforcement to dynamic efficiency, with the aim of developing innovative prediction technologies, which translate into the reduction of uncertainty associated with the production of electricity from intermittent renewable sources.

4.2.4. Burden sharing

It should be maintained among consumers an equitable distribution of costs emerging from RES-E promotion. Although, as these costs are included in the power price, similarly to what happens in Germany, with the optimization proposal electricity intensive industries are awarded a special status. This status consists of limiting the increase in costs associated with RES-E for eligible companies, whose power costs are a substantial part of their expenses. This modification guarantees that the companies competitiveness is not undermined by higher electricity costs, since the burden has a maximum limit.

5. CONCLUSION

The optimization proposal to the current national support model, although inspired in the German and Spanish ones, must take into account, once implemented, the specificities inherent to the country. The full copy of one of these models by Portugal does not guarantee that we will obtain the same results, especially if we choose to neglect national characteristics and goals.

The singularities of each country make the optimization of FIT models, through comparison with other countries, a complex task essentially due to the uncertainty scenarios related to RES-E marginal costs and benefits. This fact alone prevents the Spanish and German models from being fully implemented in Portugal.

The investment return is different depending on the country, since it depends on variables like the availability of biomass or wind potential. The attempt at model optimization by comparison, has a risk component associated to it. This is true if we underestimate that the costs, apart from being related to the specific renewable technology, are mainly interlinked with the context in which each of these technologies is applied.

The deadlines for revision and value of remuneration always depend on the position and shape of marginal costs curves. Because of this, in the proposed model for Portugal we suggest pre-established revisions and degression rates, without state that these parameters should have values equal to Germany or Spain counterparts.

At this stage, it is impossible for us to give specific values for certain parameters in the optimization proposal of the Portuguese FIT model, however we believe that the introduction of degressive tariffs and feed-in premiums, accompanied by other alterations such as, fixing the revision period and forecast obligation, may positively contribute toward the effectiveness, efficiency and equity of the model. In future, it will be interesting to empirically test the proposed model, in order to assess if the results obtained are as expected.

REFERENCES

- Decreto-lei nº 225/2007, de 31 de Maio de 2007. Diário da República. Série I. Nº105.
- European Union [EU]. (2005). *The support for electricity from renewable energy sources*. SEC (2005) 1571. Brussels: European Commission. Acedido em 9 de Novembro de 2008 em http://ec.europa.eu/energy/res/biomass_action_plan/doc/2005_12_07_comm_biomass_electricity_en.pdf
- European Union [EC]. (2008). *The Support of Electricity from Renewable Energy Sources* Accompanying Document to the Proposal for a Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources. SEC (2008) 57. Brussels: European Commission. Acedido em 24 de Maio de 2009 em http://ec.europa.eu/energy/climate_actions/doc/2008_res_working_document_en.pdf
- González, P. (2008). "Ten years of renewable electricity policies in Spain: An analysis of successive feed-in tariff reforms". *Energy Policy*, 36(8), 2917 – 2929.
- Erneuerbare Energien Gesetz, 2008 [Renewable Energy Sources Act - EEG].

- KEMA, Inc. (2008). *California feed-in tariff design and policy options* (CEC-300-2008-009D). Acedido em 6 de Junho de 2009 em <http://www.energy.ca.gov/2008publications/CEC-300-2008-009/CEC-300-2008-009-D.PDF>
- Klein, A., Pfluger, B., Held, A., Ragwitz, M., Resch, G., & Faber, T. (2008). *Evaluation of different feed-in tariff design options - Best Practice Paper for the International Feed-in Cooperation* (2nd ed.). Fraunhofer Institute Systems and Innovation Research, Vienna University of Technology Energy Economics Group. Acedido em 6 de Junho de 2009 em http://www.feed-in-cooperation.org/images/files/best_practice_paper_2nd_edition_final.pdf
- Klessmann, C., Nabe, C., & Burges, K. (2008). "Pros and cons of exposing renewables to electricity market risks – A comparison of the market integration approaches in Germany, Spain and the UK". *Energy policy*, 36(10), 3646 – 3661.
- Langniß, O., Diekmann, J., & Lehr, U. (2009). "Advanced mechanisms for the promotion of renewable energy - Models for the future evolution of the German Renewable Energy Act." *Energy Policy*, 37(4), 1289 – 1297.
- Real Decreto 661/2007, de 25 de Mayo de 2007. Boletín Oficial del Estado. Nº126.

SESSION 3.2

CREATING BETTER ENERGY STATISTICS FOR GENERATING MORE ROBUST ENERGY SCENARIO

Giampietro M. and Sorman A. H.

ARE ENERGY STATISTICS USEFUL FOR MAKING ENERGY SCENARIOS?

Bøeng A. C.

THE MAKER'S PERSPECTIVE ON ENERGY STATISTICS

Vetrella G., Femia A.

FROM BALANCES TO ACCOUNTS: A MEANINGFUL REORGANISATION OF ENERGY DATA

ARE ENERGY STATISTICS USEFUL FOR MAKING ENERGY SCENARIOS?

Mario Giampietro*¹ and Alevgul H. Sorman²

¹ ICREA Research Prof., Institute of Environmental Science and Technology (ICTA)

Universitat Autònoma de Barcelona (UAB)

² Institute of Environmental Science and Technology (ICTA)
Universitat Autònoma de Barcelona (UAB)

ABSTRACT

This paper addresses first of all the deep epistemological problem faced when attempting any energy accounting. Energy is a semantic concept which is very difficult to formalize in general terms, let alone when characterizing the complex functioning of socio-economic systems. The paper starts with a theoretical part, which explains the need of making a clear distinction between three relevant semantic categories of energy forms (Primary Energy Sources, Energy Carriers, and End Uses). Then it shows that when dealing with the analysis of the metabolic pattern of complex societies it is unavoidable to find logical bifurcations (non-equivalent quantitative assessments of the same semantic concept, when expressed in energy terms). The accounting for the energy consumption of a modern society cannot be obtained using a single number. In the second part, the paper provides a critical appraisal of the usefulness of the information of found in energy statistics. It first examines very briefly the problems associated with the conventional approach of linear representation of energy conversions, typical of old fashion statistics. Then it discusses the latest development of IEA and Eurostat which have introduced a “semantically challenging” new category of energy forms – energy commodities. This category ignores the most elementary rules of energy accounting developed in the field of energetics. Finally, the last section proposes an innovative scheme of energy accounting, which explicitly address the autocatalytic nature of energy transformations (typical of autopoietic systems) and that preserves the distinction between relevant energy forms (PES, EC; and EU) in the accounting carried out across different hierarchical levels.

Keywords: Energetic Statistics, Energetics, Energy Accounting, Energy Scenarios, Primary Energy Sources, Energy Carriers, End Uses, Metabolic Pattern of societies

1. Basic epistemological problems with accounting of energy

1.1 The huge misunderstanding about the concept of energy

Even though energy is handled by the “queen of hard sciences” – physics – energy is a semantic concept, which is quite tricky to formalize. Unfortunately, many, including a few of those working in the business of energy statistics, seem to have a very naïf view of energy and its quantification. Many seem to believe that energy is the ultimate example of an exact and deterministic variable. Since physicists have shown that it is possible to measure specific energy transformations - at a given point in space and time and after a careful setting of a measurement scheme within a controlled experimental setting – then energetic assessments expressed in Joules are considered to be very robust. This assumption is totally invalid.

The generic definition of energy: *the ability to generate a change in a given state space* is impredicative in its nature (Chemero and Turvey, 2006). That is, the pre-analytical definition of the state space (the type of changes, which can be represented in

* Corresponding author; E-mail: giampietro@liphe4.org

quantitative terms) will define the quantitative output of the accounting. However, the choice of the types of changes (the energy forms of interest) to be observed, depends on their relevance for the analysis. When travelling by car, if we want to calculate the miles we can do, it is not wise to account as useful energy inputs either incoming solar energy or French fries stored in the car. On the other hand, when travelling for three days by boat, when filling the kitchen, we neither should include gallons of gasoline among the food energy required to feed the crew, but then French fries would be relevant.

In general terms, we can say that quantitative assessment of energy can only be measured and aggregated after having agreed on a pre-analytical definition of a given set of energy forms and the conversion factors to be applied to a given set of transformation in a given setting. The aggregation of quantitative assessments of different energy forms is only possible after having agreed on two semantic decisions:

- (1) the lexicon of energy forms which will be included in the analysis (the energy graph required in engineering);
- (2) the rationale to be used to choose the criterion of equivalence (what makes it possible the definition of conversion factors in the first place).

The summing of different energy forms is like the summing of different currencies. Nobody will sum 100 US\$ to 100 € to 100 Japanese Yens into an overall sum of 300 “monetary units”. Such a sum would not carry any meaning. However, as discussed below this is a standard operation in many energy statistics (see section 2.2 of this paper about the summing of “energy commodities”). As matter of fact, the Energy Statistics Manual of the International Energy Agency literally says in the section entitled “how to calculate energy balances”: *The balance is calculated according to the arithmetic rules shown in Figure 1.3 – Pag. 30 OECD/IEA, 2004.*

Different energy forms can all be expressed in the same unit Joules or in units (kWh, kcal, BTU), but this does not necessarily imply that they can all be summed in arithmetic way. It is the decision of a criterion of aggregation (the logical definition of an equivalent class), which makes it possible the summing. Let’s imagine that we sum kg of grain, kg of fruits and kg of wood. The resulting sum would be useful for a truck driver checking the overall load of his truck. However, this very same sum would result not only useless but misleading to someone trying to calculate the supply of food, provided by that truck, to a refugee camp. As a matter of fact, energy accounting can be called as the art of choosing how to aggregate “apples and oranges” (Giampietro, 2006; Giampietro and Mayumi, 2009). As the Nobel Prize winner in physics Richard Feynman pointed out: *“it is important to realize that in physics today, we have no knowledge of what energy is... it is an abstract thing in that it does not tell us the mechanism or the **reasons** for the various formulas.”* (Feynman et al. 1963, Chapter 4, p. 2). In practice, energy can be perceived and described in a large number of *different forms*: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy, etc.

However, these are semantic categories, which can be translated into formal categories, only after choosing an adequate proxy variable within a well specified formalization (definition of a descriptive domain, scale, lexicon, boundaries). For example, the quantitative method useful to assess the energy input for a virus (based on the lexicon of biochemistry in which fuel is represented by energy-rich molecules) even if measurable in Joules, is not reducible to the quantitative method useful to assess the energy input for the industrial sector of Germany (based on the lexicon of technical energy conversions). When handling definitions and quantifications of energy obtained in different descriptive domains, any reduction and/or aggregation requires, first of all, deciding a set of criteria of equivalence (what is the equivalent of 1 J of the energy input for a virus, when expressed in 1 J of energy input to the industrial sector of Germany?).

A sentence, taken again from the explanations given in the Energy Statistics Manual on the chosen system of accounting is quite illuminating: *“For example, the gross electricity production from hydro plants is used as the primary energy form rather than the*

kinetic energy of the falling water because there is no statistical benefit from pursuing the adoption of the kinetic energy as the primary energy form (?). It does not, however, say how the amount of energy to be attributed to the primary energy form is calculated but in this case **it is natural to adopt the amount of electricity generated as the measure** (?) [question and exclamation marks are ours] - OECD/IEA, 2004 pag. 136. In this example, it is clear that without a pre-analytical structuring of the formal analysis and a definition of the logic associated with the choice of aggregation *everything goes*. The accounting becomes a series of arbitrary decisions taken by the accountant to patch here and there the available data into a protocol of accounting that does not have meaning, but which only carry out the formal task of balancing inputs and outputs in quantitative terms.

It should be noted that another classic definition of energy (found in elementary physics textbooks), is often used by many non-expert of this field, is *“the potential to do work”*. However, this definition refers to the concept of “free energy” or “exergy” (which is another potential source of confusion). Also in this case, we are in a confusing situation: both the concept of “free energy” or “exergy” can be quantified. But again this quantification can only be done within a specific, formal definition of work. Such a formal definition of work requires a clear definition of operational settings which must be necessarily referring to a given descriptive domain – scale, boundary, duration of the process to be quantified, end state, **power levels** (Giampietro and Mayumi, 2004; Mayumi and Giampietro, 2004). There is no formal definition of work which could be applied to “the activities performed in the Industrial sectors” or the “activities performed in the Household sector”, let alone if we want to consider the efficiency of the whole economy.

1.2 The definition of three semantic categories for energy forms

Primary Energy Sources – This expression refers to the energy forms required by the energy sector to generate the supply of energy carriers used by human society. According to the laws of thermodynamics primary energy sources cannot be produced. Therefore, they must be available to society, in order to make possible the production of energy carriers. Examples of Primary Energy Sources include below-ground fossil energy reserves (coal, gas, oil), blowing wind, falling water, sun, and biomass. Primary Energy Sources **are accounted in physical quantities and not in energy!!!** That is, we measure them in Tons of Oil Equivalent, kg of uranium, Tons of Coal Equivalent. This to stress the role of this accounting, which is aimed at illustrating the existence of biophysical constraints: they indicate the requirement of favourable gradients which **must be available (to be recorded into databases)**, in order to be able to produce an adequate supply of energy carriers. Any given amount of PES **can be expressed** in an energetic equivalent - e.g. 1 TOE = 42 GJ - and this is the source of the confusion found in energy statistics. In fact, this conversion requires the definition of a criterion of equivalence. In the case of TOE the criterion is the calorific value of oil, but the same criterion cannot be applied to other PES (falling water, the set of processes used to make liquid biofuels, uranium, photovoltaic).

Energy Carriers – This expression refers to the various forms of energy inputs required by the various sectors of a society to perform their functions. Energy carriers are produced by the Energy Sector of a society by using Primary Energy Sources. Examples of energy carriers include liquid fuel in a furnace, gasoline in a pump, electricity used in a factory, and hydrogen in a tank of a car. An energy carrier, therefore entails an energy cost for its production (1 MJ of energy carriers for its production requires a larger amount of energy spent in terms of MJ of PES). The distinction between “Energy Carriers” and “Primary Energy Sources” is extremely important since these two labels refer to energy forms of different quality. Like for the concept of money (it is not possible to sum US\$, € and Japanese Yens, without applying conversion factors), we cannot sum 1 kWh of electricity (3.6 MegaJoules of Energy Carriers) to 3.6 MJ of crude oil (a Primary Energy Source). In fact, electricity has a cost of production and distribution which is different from

that of crude oil. This implies that every time we perform a quantitative analysis dealing with energy accounting we must specify first of all the energy form of reference: MJ of Energy Carriers are not the same as MJ of Primary Energy Sources!

Energy end-uses – This expression refers to the useful tasks/works performed by the various sectors of society when converting energy carriers into applied power. Examples of end-uses include moving goods, melting iron, building a road, regulating traffic by moving hands, and air-conditioning of a room.

1.3 The unavoidable bifurcations in energy data found on existing energy statistics

In this section we want to use a practical example to show the unavoidable emergence of bifurcations in the quantitative accounting of energy transformations, when representing the pattern of energy metabolism of a country.

In Fig. 1 we use an overall representation of the network of energy consumption of Spain (in 2005) to illustrate this point.

Fig. 1 The flows of energy consumed in Spain quantified using: 2 semantic categories - Primary Energy Sources (PES) and Energy Carriers (EC). Then 7 formal categories [coal, oil, natural gas, nuclear, hydro, solar&geo, other renewables] in PES and 3 formal categories [electricity, heat and fuel] in EC.

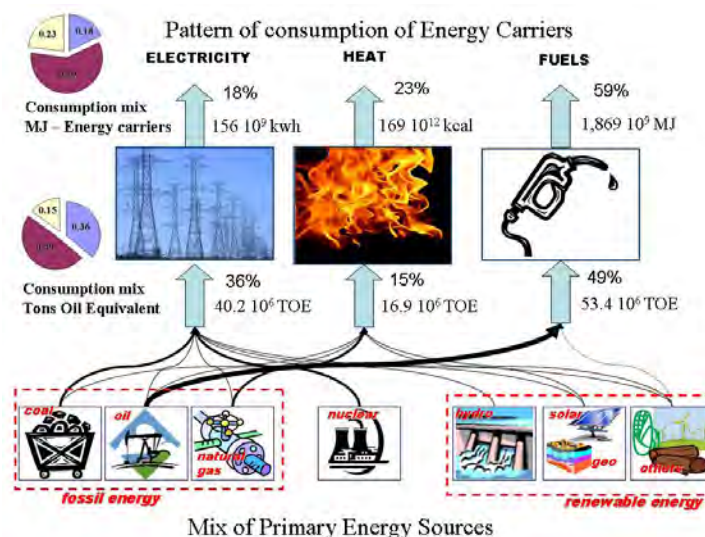


Figure 1. The PES and EC mix of Energy Consumption for Spain 2005

Let's now go through the information given in Fig. 1 starting from the bottom.

On the bottom of the figure we find the given MIX of different types of Primary Energy Sources (Semantic Category) which are required to power the energy sector. Starting from the left we have 7 different formal categories of PES [which can be divided into 3 sub-semantic categories: (A) Fossil Energy Sources (non-renewable) represented by: 3 formal categories - coal, oil and natural gas. In the middle we have: (B) Nuclear Energy (difficult to define in relation to its degree of renewability). On the right we have: (C) Renewable Energy Sources represented by 3 formal categories: hydro, solar and geo, wind and biofuels.

As observed earlier, since these 7 formal categories refer to the same semantic category (PES) it is possible to aggregate their value, by adopting a protocol of accounting (production rules). The quantitative assessment of the total amounts of energy from different PES, which is used in the energy sector to produce energy carriers, can be expressed in a common unit of measurement – but it requires the selection of a standard formal category used as reference – i.e. Tons of Oil Equivalent. The overall total must be

expressed in MJ of a given formal category of reference and therefore it must be in the form of $\rightarrow$ MJ of “formal category x” equivalent.

In the middle of the figure we find the quantitative representation of the MIX of different Energy Carriers produced by the Energy Sector and consumed by society. This is another semantic category referring to the particular attributes that these energy forms must have in order to guarantee the end uses required by society. The three (broadly defined) formal categories of energy carriers are: (i) Electricity; (ii) Fuels; and (iii) Heat.

To underline the difference ***in quality*** between these the numerical assessments of the amount of energy calculated using the three different formal categories of energy carriers we decided to express the different amounts of energy referring to each one of these different energy carriers, using different units of measurement. In particular, the three units are: (i) kWh for measuring electricity; (ii) kcal for measuring heat; and (iii) MJ for measuring fuels.

The assessments expressed using these different units of measurement can be reduced to each other using conversion factors [1 kWh = 3.6 MJ; (ii) 1 kcal = 4.186 kJ].

Then, it becomes possible to use a common unit (Joules) to calculate two important pieces of information: (A) the total amount of energy consumed by society in the form of energy carriers – expressed in MJ_{EC}; and (B) the profile of the relative percentage of the three energy carriers in this total.

However, if we do so, we get the bifurcation in the possible quantifications of the energy consumption of Spain, illustrated in Fig. 1. That is, when we generate a quantitative assessment of energy consumption using the semantic category – energy carriers – then the resulting numerical value is not equivalent to the one discussed in the previous paragraph. The total consumption of energy of Spain (expressed in MJ of Energy Carriers) ***refer to an energy form of reference*** (the semantic category EC) which is non-equivalent to the energy form of reference (the semantic category of PES) used for the assessment of Tons of Oil Equivalent!

As easily observed when looking at Fig. 1 there are two non-equivalent quantifications of the mix of energy carriers used by Spain. That is, in the figure there are two pies of different size, providing a different profile of percentages characterizing the relative use of the three energy carriers. Looking at the two pies on the left-upper part of the figure we can see that is we use:

(A) when using Tons of Oil Equivalent for the quantitative assessment (based on the consumption of Primary Energy Sources) then: 4.6 ExaJoules of PES are consumed and 36% of this energy goes in the making of electricity;

(B) when using MJ of energy carriers for the quantitative assessment (after eliminating from the accounting the conversion losses) then: 3.1 ExaJoules of EC are consumed and only 18% of the energy spent in Spain is in the form of electricity (when converting the three different units in MJ and without applying any quality/conversion factor).

Needless to say, that this bifurcation in the quantitative assessments of the same semantic concept (a representation of how energy is used in Spain) is a natural phenomenon. There is nothing wrong with it, but, in fact, has to be acknowledged. As discussed below, the dataset of BP, IEA and Eurostat presents just a single set of numbers, which is perfectly balanced, and which is based on the accounting and summing together of items belonging to the two semantic categories of Primary Energy Sources and Energy Carriers. This is certainly a reason for concern.

The second observation to be made about Fig. 1, refers to the implications of the structure of the network of energy transformations. In fact, not all the MJ of fossil energy (formal categories within the semantic category PES) are the same. It is well known that 1 MJ of natural gas is more effective than 1 MJ of oil, and 1 MJ of oil is more effective than 1 MJ of coal. Therefore, the same amount of Total Energy Throughput (expressed in Joules of PES) can have different effects on the economy depending on the profile of distribution of the total amount of Tons of Oil Equivalent over the set of 7 formal

categories. In this regard, it is well known that in the last decades for developed countries, an important factor determining the increase in performance of the economy has been a continuous adjustment in the mix of Primary Energy Sources (Hall et al. 1986; Ayres et al. 2003) - oil replaced coal and now natural gas is replacing oil. The same phenomenon took place in relation to the mix of energy carriers (the upper pies on the left). The post-industrialization coincides with a continuous adjustment in the mix (relative importance of the 3 formal categories) of Energy Carriers (Ayres and Warr, 2005). The fraction of electricity (due to its versatility and convenience in terms of instant access) has been continuously expanding now for decades within the pie of energy carriers.

So if we want to study the changes in the efficiency of the economic process in terms of energy analysis, it is essential to be able to study changes in both pies, addressing the implications of both: (i) changes in PES (affecting the seriousness of external constraints); and (ii) changes in EC (affecting internal efficiency in the conversion of energy carriers into end uses).

To make things more difficult, the amount of energy accounted over the various formal categories (7) included in the category PES are not all equally useful for generating all sorts of energy carriers for the society. For example, nuclear, hydroelectric and wind power, at the moment, can only generate electricity. Depending on the particular mix of energy carriers required for a given task, this may represent a problem. In fact, even if electricity is the most valuable among the energy carriers potentially used in every energy consuming sector, there are some tasks (e.g. powering a jumbo airplane), which cannot be performed using electricity and currently only depend on jet fuel Smil (2003). Therefore, it is important to be aware of the importance of considering the various connections over the network of energy transformations shown in Fig. 1: who is producing what on the supply side and who is consuming what on the consumption side.

This entails two distinct feasibility/viability checks:

(1) a check on the feasibility of the energy sector (supply side) - the mix of 7 formal categories, included in the semantic category **Primary Energy Sources** has to be able to match in terms of supply the requirement of the mix of 3 formal categories, included in the semantic category **Energy Carriers**; which is required by society (EXTERNAL CONSTRAINTS);

(2) a check on the viability of the metabolic patterns of society (consumption side) - the mix of 3 formal categories, included in the semantic category **Energy Carriers**, has to be able to match, in terms of supply, the requirement associated with the mix of formal categories of functions to be carried out by the end uses for the sustenance of the society, included in the semantic categories **End Uses** (INTERNAL CONSTRAINTS).

This observation is very important if we want to use energy data to discuss of possible alternative future energy scenarios, no longer based on fossil energy.

2. A critical appraisal of the actual system of accounting in energy statistics

2.1 The old fashion representation of energy consumption of developed countries

The old-fashion characterization of national energy consumption, for the purpose of energy accounting, is still very popular. An example of the standard map-flow (mapping the chains of energy flows in the form of a sankey diagram) is given in Fig. 2. This example is taken from the Energy Information Agency of the USA, and it refers to the energy balance of USA in 2001.

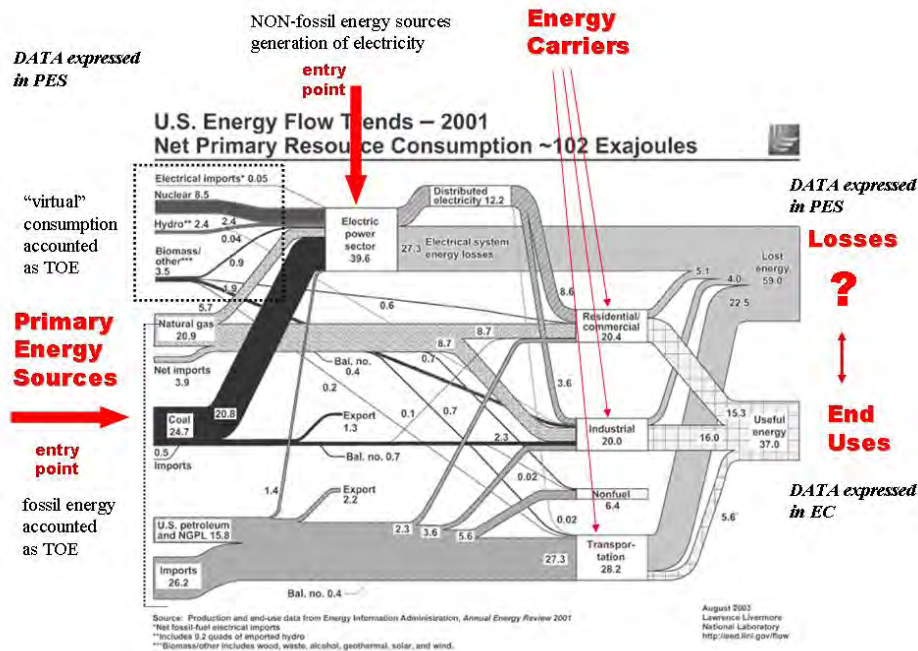


Figure 2. Linear map-flow of energy consumption in the USA 2001

What is important to observer in this figure is the choice of adopting **a linear representation** of the various flows. The representation is based on the idea that you have energy forms entering the system from the left side, then these energy forms are transformed (in the middle) and they are finally used on the right side of the graph - with the input numbers perfectly adding up to the output numbers throughout the linear mapping. This implies that during this trajectory the energy flows considered in the analysis **must change both their values and their identity**, across the linear trajectory, which starts form left and end to right. Assuming that it is possible to perform this quantification, therefore, means assuming that it is possible to define in a substantive way (semantic and formal, with no uncertainty and disagreement among the users of data) the series of two conversions: (A) Primary Energy Sources → Energy Carriers (when moving from the left to the center of the figure); and (B) Energy Carriers → End Uses (when moving from the center of the figure to the right). We claim that this assumption is not valid. As illustrated in Fig. 1, the conversion (A) PES → EC can be quantified in two non-equivalent ways (depending on the energy form we decide to use are reference, either PES of EC); and the conversion (B) EC → EU cannot be quantified at all, since the proxy variables needed to quantify End Uses (the work done in the different final compartments) are not commensurable with the proxy variables needed to quantify Energy Carriers.

Looking at Fig. 2 in details, we can see on the left of the graph a quantity of primary energy sources (semantic category - PES) which then becomes a flow of energy carriers (semantic category - EC), in the middle. The logical difference between the semantic categories PES and EC entails an unavoidable amount of energy losses (second law of thermodynamics) due to the transformation PES → EC. Finally, the linear flow ends (on the right of the graph) with the definition of yet another semantic category End Uses. It should be noted though, that in this representation, the formal representation of “energy losses” (the quantitative representation) is located on the right of the graph, for balancing the accounting, as if it were playing the same role of end uses. Moreover, with such a representation, it is quite impossible to interpret what kind of losses this aggregated quantity refers to. (e.g. transformational, distributional?). In fact, the balancing of the accounting (done using numbers referring to formal categories) over the chosen set of semantic categories is everything but easy . . .

What can we do with the quantitative information found in energy statistics of the type illustrated in Fig. 2?

In relation to the two numerical values of PES and EC we can say:

(a) The total amount of energy consumption, expressed in PES (found on the left of the graph) is useful for comparing the total consumption of countries, in relation to a given PES of reference [= Tons of Oil Equivalent]. However, even if we adopt (as reference) a given category of PES such as Tons of Oil Equivalent, then we have a problem with the electricity which enters into the system from the top (hydroelectric, nuclear, photovoltaic) – that is, the electricity not produced with fossil energy – which can no longer be expressed in Tons of Oil Equivalent, unless we invent a “virtual” consumption of TOE which would be required to produce this electricity using virtual conventional power plants fed with fossil energy. In this way we can generate a number (as done by BP, IEA statistics) which can only provide a meaningful comparison in relation to the importance that the production of electricity with non-fossil energy PES plays in different economies. For example, if a country like Sweden produces a very large fraction of electricity using hydroelectric power, by adopting an accounting based on EC (referring to the physical energy content method in use by international statistics¹ – where for example hydroelectricity is valued by the energy content of the electricity converted to primary energy directly (1 MWh = 0.086 toe)), it would seem that Sweden uses much less energy than other countries. Whereas by adding a virtual consumption of TOE (as done by the partial substitution method (the old IEA method) – for hydro and nuclear electricity are both valued by the primary energy which would be needed to obtain them, if fossil fuels were used, at an average efficiency of 38.5% (thus; making 1Mwh = 0.086 toe/0.385) equivalent we correct with a quality factor the larger presence of MJ of electricity in the mix of energy carriers.

(b) IF we would use only the total amount of energy consumption expressed in EC, THEN the resulting characterization of consumption, both in absolute value and in percentage over the pie, will not reflect either the total initial consumption of energy – expressed in PES – nor the final achievement in terms of end uses.

2.2 A few problems with the actual system of accounting in Eurostat statistics

When reading the explanations of the system of accounting adopted for generating the Energy Balances by both the International Energy Agency and Eurostat it is difficult to understand the logic used for organizing the dataset. As a matter of fact, the basic framing is similar to that adopted by BP energy statistics (linear), however, the semantic used for the choice of categories is not clear (at least for us).

The first problem comes with the semantic concepts used to define what type of information is given with the dataset. For example, the dataset uses the expression of “**energy commodities**” and “**commodities balance**” to justify the summing of different forms of energy without defining conversion factors. This is like aggregating different currencies (US\$, € and Japanes Yens) into a common category “monetary units” and then summing them as such. How robust is the semantic behind the chosen protocol of accounting for energy transformations? A few examples are discussed below:

#1 The confusing handling of the category Primary Energy Sources

The semantic associated with the concept of Primary Energy Source is pretty straightforward. It derives directly from the application of the fundamental laws of thermodynamics. Human technology can not produce energy. Human technology can only use a given source of primary energy (a useful gradient of something, found already in the environment) to generate energy carriers. The problem is that the various categories of PES cannot be aggregated and compared as such. In fact, each one of the considered categories of PES (e.g. the 7 categories considered in Fig. 1) provides a certain amount of either kWh of electricity, kcal of heat or MJ of fuels (the OUTPUT), and consumes

¹ OECD/IEA, 2004

different amounts and types of INPUT – e.g. kg of uranium, or cubic meter of water, or hours of winds or cubic meter of natural gas (the primary energy).

In order to be able to sum together quantitative assessments of energy referring to different formal categories of PES we have to adopt some logical criterion of equivalence for both the output and the primary energy. The logic to be used for this choice will determine the semantic category in relation to which we want to perform the aggregation. If we want to aggregate these different quantitative assessments in relation to their CO₂ emission (the OUTPUT), then we have to adopt a given production rule (introducing semantic sub-categories – fossil energy PES vs. non-fossil energy PES). If we want to aggregate these different quantitative assessments in relation to their labour demand (total workers required by the energy sector to deliver the required supply of energy carriers), we will have to aggregate the various PES using a different production rule, and so on. The IEA and Eurostat does not have any logic criterion of aggregation (even though it does aggregate a lot of numbers in just one way).

#2 The confusing handling of the relations between semantic and formal categories

The most disturbing fact, is that this label of “energy commodities” seems to refer indistinctly not only to: (i) different semantic categories (both PES and EC); but also to (ii) different formal categories within each one of these semantic categories.

In fact, the proposed system of accounting is based on a distinction between: “Primary Energy Commodities” and “Secondary Energy Commodities”. However, this choice of categories generates a serious epistemological impasse, since, with this choice of category, the generation of electricity from hydroelectric or nuclear (an assessment which is based on the amount of electricity generated by the plants) is considered to be a “Primary Energy Commodity”. As a matter of fact, the IEA/OECD Energy Statistics manual states that, summing both primary and secondary production in the commodity balance “has the advantage of presenting all commodities identically without requiring the user to know that there are two locations in which production information is presented” (!) (IEA/OECD, 2004, pg 140) That is by suing this label the accounting of the relative amount of electric energy (based on the direct measurement expressed in MJ of energy carriers) is included in the same category where we find coal, natural gas and oil (assessments based on the direct measurement of tons of coal, cubic meters of natural gas, tons of oil, expressed in natural units). Therefore, in Eurostat and IEA statistics the summing of the various formal categories (the numerical values expressed in energy units) included in the “semantically undefined” category “Primary Energy Commodities”. Within this very same category the kWh of electricity are accounted in different ways! Those from nuclear plants are multiplied by 3 - or by another conversion factor when available - those from hydroelectric plants are not multiplied at all (as discussed in section 2.1 with the great differences between the physical energy content method - currently in use by international statistics - and the partial substitution method). To clarify better the implications of this choice, we have to note in the latter case we have that kWh of hydroelectricity are simply summed to tons of oil! To make this conversion the proposed protocol uses the energy equivalent of a ton of oil (1 TOE = 42 GJ) and the value of a kWh (kWh = 1,000 J/sec x 3,600 sec = 3.6 MJ), with the bizarre result that 1 kWh of electricity (an energy unit used to assess an energy carrier) is summed to 1 Ton of Oil (a natural unit expressed in mass). The resulting conversion factor (to move from tons of oil to kWh of electricity) is the calorific value of 1 ton of oil! We can only say that this choice is disturbing for engineers and physicists. In fact, when moving from the 42 GJ of heat associated with a ton of oil to an equivalent amount of electricity **one must necessarily assess also the efficiency of the conversion of heat into mechanical power - required to generate electricity!** (about 30% of EC energy out over PES energy in). This piece of information is not only needed to calculated losses and conversion factors over energy flows, but also to establish a relation between other relevant natural units – kg of coals, kg steam in the turbine, kg of CO₂ emissions, water vapour, SO_x emissions, etc. The use of the category “energy commodity” destroys all this information.

3. Can we generate energy statistics more user friendly for scenarios making?

In Fig. 3 we indicate the various pieces of information required, at different levels of analysis, to provide an effective characterization of the various transformations associated with the expression of the metabolic pattern of modern economies (integrating at a large scale the information given in Fig. 1).

Starting from the left of the figure, we can see:

Point # 1 - characterization of the different typologies of Primary Energy Sources – using a set of formal categories (in this example we stick with the 7 illustrated in Fig. 1, but obviously this choice may be discussed). This characterization has to be done by using both non-energy variables - tons of coal, kg of uranium, tons of water, hectares of land – and energy equivalent. In this way it becomes possible to assess the relevance of external constraints, which affect the potential supply of energy carriers, using specific indicators for the various typologies of PES considered (for each MJ of energy carriers generated). This information is essential for discussing of energy scenarios no longer based on fossil energy;

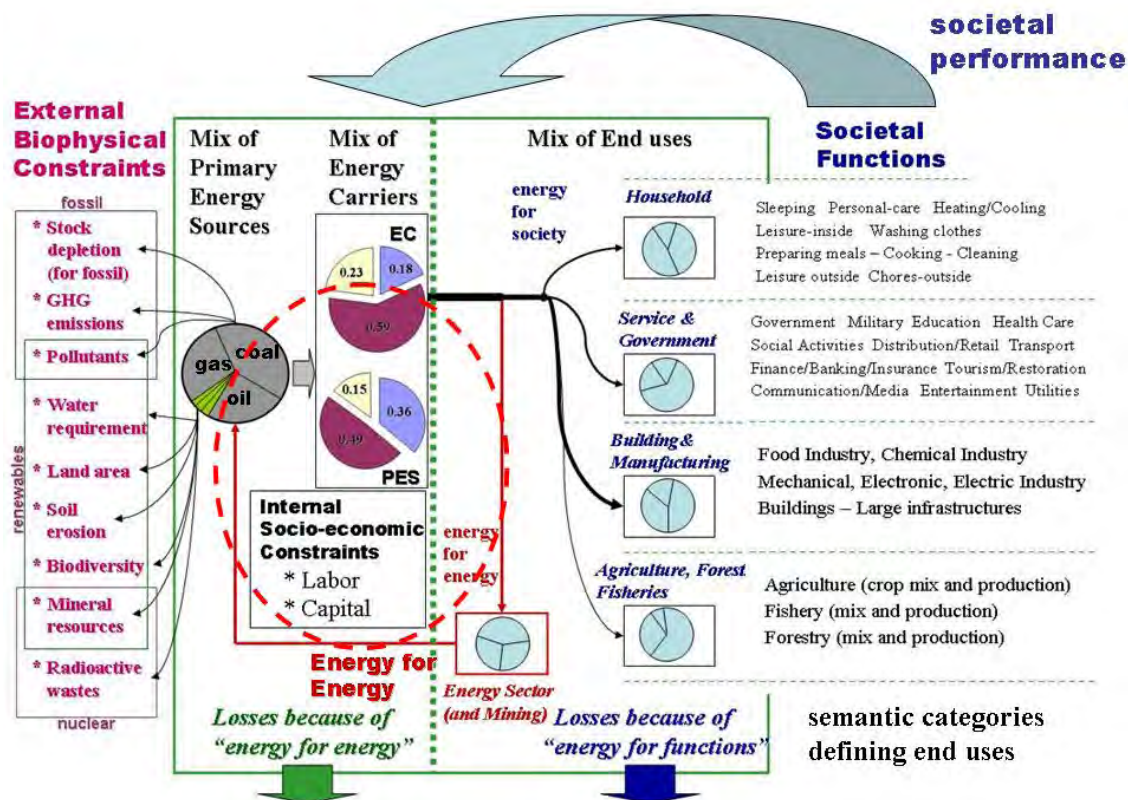


Figure 3. The autocatalytic loops of energy transformation within societies

Point # 2 - characterization of the type of energy carriers supplied by the various typologies of PES. This requires a graph indicating the connections over the relative flows of energy carriers. This information has to be complemented by the relative characterization of their technical coefficients (refer to Fig.1 for details);

Point # 3 - establishing a relation between the MIX of PES and the relative MIX of EC. In this first assessment, we quantify the MIX of EC using MJ of PES equivalent. In this way, we assess the performance of the energy sector over the conversion PES → EC.

Point # 4 – establishing a relation between the MIX of EC and the MIX of EU. Starting from the record of the total amount of MJ consumed for each energy carrier and

the profile over the mix one can perform an analysis of the metabolism of the various sectors of the economy based on the direct flow of energy carriers (see the paper Sorman and Giampietro presented at this same conference within the proceedings). In this way it becomes possible to establish a relation between the dataset developed in energy balances and the analysis of the pattern of metabolism of modern societies.

Point # 5 - calculating the profile of consumption of energy carriers (mix and amount of each of the carriers) per each one of the relevant compartment of the economy: Household, Agriculture, Productive Sector (called there Industry); Service and Government, including the energy sector (see next Point #6). In this way, we can assess the performance of the socio-economic system over the conversion $EC \rightarrow EU$.

Point # 6 - providing the crucial information about the consumption of energy carriers (mix and amount of each of the carriers) **used in the energy sector**, which is determined by the exploitation of the given mix of 7 categories of PES. This information is crucial since it makes it possible to calculate the overall EROI – Energy Return On the Investment - the “biophysical costs” for generating the required supply of energy carriers in the other compartments. The energy consumed by the energy sector, **should not be considered as a generic loss to be summed to the others!** Rather it is a valuable information about the required investment of energy, which is needed to make it possible the production of energy carriers (Fig. 3).

In this way, we can **finally assess the performance of the socio-economic system over the autocatalytic loop of conversions: $PES \rightarrow EC \rightarrow EU \rightarrow PES$** . Ultimately with such a representation, we are **no longer representing a linear set of energy transformations, but the basic autocatalytic loop of non-equivalent energy forms, needed to generate and stabilize the metabolic pattern of modern societies!** Energy carriers are used also to make themselves (taking advantage of the gradients provided by Primary Energy Sources) and in this autocatalytic loop they generate a surplus, which can be used by society to stabilize the structures/functions expressed in the various compartments of the society.

Conclusion

Using the scheme of Fig. 3 it is possible to use available energy data to generate a description and characterization of the pattern of production and use of energy carriers associated with the expression of the required set of functions expected in a modern society. All the information needed to make such a description is already available to statistical offices. However, these data are at the moment processed using dubious (see to sections 2.1. and 2.2) production rules to generate a quantitative representation which, in our view, does not provide the required information to generate informed and robust scenarios, especially when looking for different metabolic patterns in the future.

REFERENCES

- Ayres, R.U. and Warr, B. (2005) ‘Accounting for growth: The role of physical work’, *Structural Change and Economic Dynamics*, vol 16, no 2, pp 181-209
- Ayres R.U., Ayres L.W. and Warr B. (2003) ‘Exergy, power and work in the US economy, 1900-1998’, *Energy*, vol 28, no 3, pp 219-273
- Chemero A. and Turvey M.T. 2006 “Complexity and “Closure to Efficient Cause”” In: K. Ruiz-Mirazo and R. Barandiaran (eds.), *Proceedings of AlifeX: Workshop on Artificial Autonomy*
- Feynman, R., Leighton, B. and Sands, M., 1963. *The Feynman Lectures on Physics: Mainly Mechanics, Radiation, and Heat, Volume I*. Addison-Wesley Publishing Company, Menlo Park, California.
- Giampietro, M. (2006) ‘Theoretical and practical considerations on the meaning and usefulness of traditional energy analysis’, *Journal of Industrial Ecology* vol 10, no 4, pp 173-185
- Giampietro, M. and Mayumi, K. (2009) *The Biofuel Delusion: The Fallacy of Large-scale Agro-biofuel Production*, London: Earthscan.

- Giampietro, M. and Mayumi, K. (2004) 'Complex systems and energy', in C. Cleveland (ed) *Encyclopedia of Energy*, vol. 1, Elsevier, San Diego, CA, pp. 617-631
- Mayumi, K. and Giampietro, M. (2004) 'Entropy in ecological economics', in J. Proops and P. Safonov (eds) *Modeling in Ecological Economics*, Edward Elgar, Cheltenham, UK, pp 80-101
- Hall, C.A.S., Cleveland, C.J. and Kaufman, R. (1986) *Energy and Resource Quality*, John Wiley & Sons, New York
- OECD/IEA, 2004, *Energy Statistics Manual*, Available Online: http://www.iea.org/textbase/nppdf/free/2004/statistics_manual.pdf
- Smil, V. (2003) *Energy at the crossroads: Global Perspectives and Uncertainties*, MIT Press, Cambridge, MA

THE MAKER'S PERSPECTIVE ON ENERGY STATISTICS

*Ann Christin Bøeng**

Statistics Norway

ABSTRACT

Detailed, complete, timely and reliable statistics are essential to monitor the energy situation at a country level as well as at an international level. Energy policy decisions, energy efficiency indicators, comparison between fuels, energy security and dependency, and econometric models for forecasting and planning future investments constitute just some examples of other needs for sound energy information. The climate crisis has also enhanced the need for more and more detailed, and reliable energy statistics. The introduction of tradable quotas for GHG emissions in many countries require solid estimates of emissions, and therefore sound energy data, as considerable sums of money is involved. This is also the case with EU's recently approved renewable energy directive which set targets for the countries' renewable energy shares in 2020, and which can be rather costly for these countries. The topic for the 7th biennial international workshop on advances in energy studies, is "Can we break the addiction to fossil fuels". This is an important issue, both because we want to reduce emissions, and because fossil fuels are limited and thus will come to an end. It is not unlikely that we will experience scarcity or lack of oil and gas during this century if fossil fuel consumption continues to increase in the same accelerating speed as it has done since the industrial revolution in the 18th century. To be able to evaluate the usefulness of statistics as a tool in the fight against climate crisis and addiction to fossil fuels, one should have a better understanding of the weaknesses in statistics. What do energy statistics show, how reliable is it, what are hidden behind the figures and how should we interpret statistics and indicators. Some of the issues that are elaborated on are work situation among statisticians, problems with data collection, statistical differences, multiple data sources, methodologies, and losses of energy. Some challenges related to carbon leakage, transport, and biofuels are also mentioned.

1. Challenges that energy statisticians face

While the needs for energy statistics has increased, it has of different reasons, become more and more difficult to provide a timely and reliable picture of the energy situation in many countries. The energy market is complex, and is changing all the time. New energy forms and technologies and new large consumers or producers of energy are constantly introduced.

The liberalisation of energy markets brings new challenges to energy statistics. Firstly, the multiplication of market interveners: where statisticians in the past could get detailed information on one fuel (gas or electricity) from one national utility, they have now to survey tens or hundreds of companies to obtain a comprehensive overview of a sector. Secondly, market regulations generally lead to confidentiality issues which add the difficulty of collecting basic information where there are few players. In many countries, the legal framework for collecting statistics has not evolved to meet the new challenges inherent to the energy market liberalisation. In Norway, the Central bureau of Statistics (Statistics Norway) can collect data from industry and commerce with authorization according to the Statistics Act, and can issue a penalty for those who do not respond to their questionnaires. However, far from all countries have this kind of legal framework.

* E-mail: abg@ssb.no; Phone: 004721094743

The consequence is more estimates and more missing data as well as longer delays in obtaining the data, and therefore also a loss of information, quality and timeliness.

As statistics are often perceived to have a low profile, it has a limited appeal to young professionals and attracts few champions. Work on statistics is often a first job after ended studies, and used as a springboard to other careers. The impact of lacking resources is therefore not only limited to the quantity of the human resources but also to the quality of these resources. At the same time, additional data requirements have been, and continue to be passed on to energy statistics offices over the years.

1.2 Biofuels and harmful effects

1.2.1 Biomass

Beside hydro power, biofuels are the most important alternative to fossil fuels. However, biomass, which represents more than 10% of total primary energy supply in the world, is one of the most difficult fuels to monitor in terms of supply and demand, partly because most of the wood is not commercialized but instead collected for own use. Furthermore, it is seldom that people have exact information about how much fuelwood they have used. In addition, the energy contents in fuelwood can vary a lot, depending on the quality of the wood, the density, how dry it is etc., something that makes conversion from mass or volumes of wood to energy units such, as joule, uncertain.

1.2.2 Liquid biofuels

The production and consumption of liquid biofuels for transport have increased considerably in recent years, as a substitute for fossil fuels. It is likely that the share of liquid biofuels will continue to increase due to national regulations demanding increased share of biofuels in transport, and the renewable energy directive which imposes EU countries to increase their share of renewable energy in the transport sector to 10 per cent within 2020. However, the production of biofuels has certain negative consequences. Today, most biofuels are produced by products that alternatively could be used for food production, and can with that lead to shortage of food or to increased food prices. In addition, the production of biofuels involves changes in land use that might give CO₂ emissions, for instance if rain forests are transformed into agricultural areas. In order to mitigate the negative side-effects caused by biofuels production, the countries have to verify that the biofuels are produced in a sustainable way. The EU commission has planned to launch a new set of sustainability criteria in 2011, where the purpose is to take the negative effects into consideration. Due to the problems with today's liquid biofuels, the so-called second generation liquid biofuels, based on wood waste or straws, has been promoted. This type of raw material cannot be used in food production. However, there are also some challenges related to the use of second generation liquid biofuels.

Trees and plants act as a storing place for CO₂, and when these are cut, the stored carbon will be released into the atmosphere. All biomass is considered to be CO₂ – neutral, even though CO₂ is emitted through wood combustion. The argument is that new trees replace those that are cut down. This is a truth with modifications, especially for trees with a long life cycle which take a long time to replace. Statistics on biofuels and biomass do usually not show these kinds of aspects or the impact of changes in land use.

1.3 Multiple data sources

Data on the same variable, submitted by different national sources, are not identical. Because different data sources often are used in different statistics or by statistics offices and organizations, statistics that should be equal in fact differ. It can even be difficult to harmonize data sources within a statistics office because some statistics are based on data from the energy consumers, for instance sample surveys on energy consumption in households or manufacturing industries, while other statistics are based on data from

suppliers of energy such as electricity plants. It is seldom that data reported from users and suppliers of energy are identical.

Another common problem is the lack of coherence between energy value figures in the National Accounts and corresponding energy quantity figures in energy statistics. The main reason is that the National Accounts uses data sources that report figures in values while the energy statisticians use data sources that report in physical quantities. Combining energy statistics, economic variables and energy values and taxes from the National Accounts and emissions from energy use, is essential in many macro economic research models and in studies of economic and environmental accounts. When dividing value figures for different sectors on the corresponding quantity figures, you should ideally get a reasonable set of energy prices, but this is seldom the case. This indicates that some of the data, either for values or physical quantity are wrong, and a wrong statistics basis lowers the quality of research models. This could again affect energy policy decisions because the results from these kinds of models are often used as background information.

Energy balances and energy accounts in physical quantities

The energy balances gives an overview of the energy supply, trade, stocks, transformation and demand by sector and all energy products in a country. It is an important source for modelling and forecasting, to understand the energy security situation, to provide a basis for energy indicators and estimation of CO₂ emissions as well as to be used as basis in energy policy. Energy accounts are presented in a similar table, but it is compiled according to the definitions and principles of the National Accounts. It is still not developed any recommendation for standardised energy flow account tables, but according to Norway's physical energy flow account and the current proposals for standards, for instance in SEEA Energy (System of Environmental-Economic Accounting for Energy) which currently is being drafted, the main differences to be addressed are the following:

- Use of the territorial principles in energy balances versus the residence principle in energy accounts. The energy account reports the energy consumption from economic activity in the same way as the National Accounts. This implies that energy used by the countries transport trades and tourists abroad are included, while the energy used by foreign transport industries and tourists in the country is excluded. The energy balance follows the flow of energy within the national territory.

Energy used for transport purposes and non-energy use is included in a separate category for transport and non-energy use respectively in the energy balance, while the energy account usually places the consumption of all energy under the actual consumer sector, regardless of whether consumption refers to transportation, heating, processing or non-energy use.

The energy accounts and balances are sometimes regarded as competing tables for energy supply and use. However, these tables could rather be regarded as complementary tables, showing different aspects. They are mainly based on the same data, but the data are organised in different ways. It is sometimes difficult to get reliable information on some of the specific data that are necessary for the energy accounts, such as transport trades purchases of energy abroad. This is instead often estimated.

1.4 Statistical differences

The energy balance combines energy supply, conversion losses, and demand in one single table, and this is supposed to be in balance (as the name "energy balance" indicates). If all data sources were correct and consistent, the supply would equal the consumption. However, statistical differences arise from the collection of data from different parts of the fuel flow, from its supply origins to the various stages of downstream conversion and use. These are a normal part of a fuel balance.

Large statistical differences (it should be less than 1 per cent for major energy commodities) are of many reasons problematic. First of all, because it indicates that some of the data are wrong. Secondly, you do not know which data to rely on when you calculate emissions. It is a good practice to apply both a sectoral approach and the reference approach to estimate a country's CO₂ emissions from fuel combustion and to compare the results of these two independent estimates. The reference approach is a top-down approach, using a country's energy supply data to calculate the emissions of CO₂ from combustion of mainly fossil fuels, while the sectoral approach is a bottom-up approach based on consumption data. Large statistical differences result in significant differences in the CO₂-emissions calculated by using these two approaches, and it leads to uncertainty surrounding the actual emissions in the country. A third problem is that statistical differences are not accepted in the National account, and due to that, principally neither in the energy account. However, because the energy account is based on the same data as the energy balance, it is just as difficult to avoid statistical differences in the energy account as in the balance.

National statisticians should investigate large and persistent statistical differences in order to establish which data are wrong or incomplete. However, it is not always easy to find an explanation for the statistical differences. It could be systematic erroneous reporting from large users or producers of energy, or it could be different delimitations or contents of the energy products on the user and supply side. It can for instance be difficult to separate between different kinds of oil products, both on the supply and the consumption side.

1.5. Definitions and conversion factors

Data for physical flows are usually collected in their natural unit, such as tonnes or litres for oil products, GWh for electricity, m³ for fuel wood etc. In an energy balance we want to convert the energy commodities to a joint unit, such as joule, to allow comparison across energy products and to obtain a total. This requires a reliable set of conversion factors and information about the calorific value (energy contents) and the density in the fuels in the country. However, the calorific value can vary widely between fuels within the same category, such as different kinds of biomass (birch trees, wood waste etc), or between crude oil from different fields, and it is hard to get a complete overview of the various uses. Furthermore, the set of conversion factors used in countries and organizations can vary. It can be correct to use different conversion factors in different countries, because they might in fact vary among countries. The variations could also be a result of different traditions in countries and organisations, and lack of information about the actual conversion factors.

To make it even more complex, the calorific value can be measured as either gross or net, where gross calorific value (GCV) measures the total amount of heat that is produced by combustion. Part of the heat is locked up in the latent heat of evaporation of any water present in the fuel before combustion, and this is included in the GCV. The net calorific value (NCV) excludes the latent heat and is the amount of heat which is actually available from the combustion process. The difference between NCV and GCV is especially high for fuelwood (more than 10 per cent), due to its high moisture content. It is recommended to use NCV since most current technologies are still not able to recover the latent heat in energy. In reality, some countries use GCV while most use NCV. In Norway, it has been a tradition to use both; GCV for natural gas and NCV for other energy commodities. Different traditions for using GCV and NCV are another reason for why statistics are not comparable.

1.6 Definitions and methodology

Definitions of energy flows and products vary among different countries, statistics offices and organizations, and this makes it difficult to compare different countries' energy

statistics. Methodological approaches, or data collection methodologies, are not standardized throughout the world. Each country and organization has its own convention when building commodity balances and energy balances. For instance, some continue to use the partial substitution methodology when building their energy balances while others have adopted the physical energy content methodology. This leads, for instance, to major differences in the share of hydro-electricity in total primary energy supply. This is elaborated on in more detail below.

1.6.1 The partial substitution method

In the earlier days of energy balance methodology the IEA and Eurostat used a partial substitution method to value primary energy production. This method, which still is used by some countries, gives the electricity production an energy value equal to the hypothetical amount of the fuel required to generate an identical amount of electricity in a thermal power station using combustible fuels. However, because of the lower efficiency of thermal power generation (typically 36 or 38%, but this coefficient can vary), a far larger amount of energy in the form of fuels is required to compensate for the electricity lost from hydro plants. This imbalance was overcome by substituting for hydro production, an energy value nearly three times (for instance $1/0.36$) its physical energy content. This method has little meaning for countries in which hydroelectricity generation is the major supply.

It was a lot of countries and organizations using the partial substitution method 20 years ago, but they have gradually changed to the physical energy contents method. However, this method is still used by some actors and countries, such as BP (British Petroleum statistical review), USA and Japan. BP uses in addition the gross production as an approximation for consumption, without accounting for imports and exports of electricity. For Norway, which has a very high hydro electricity production and much electricity trade, these methods imply that electricity consumption becomes 3 times higher according to BP-statistics, than in IEA statistics; respectively 31,8 and 9,6 million of tonnes oil equivalents in 2008.

1.6.2 The physical energy content method

The principle that is now adopted in IEA, Eurostat and most countries, is the "physical energy content" method in which the normal physical energy value of the primary energy form is used in the production figure. For primary electricity, this is simply the gross generation figure for the source. However, for other energy sources, such as nuclear and geothermal, a heat equivalent is calculated. In the case of electricity generation from primary heat (nuclear and geothermal), the heat is the primary energy form. As it can be difficult to obtain measurements of the heat flow to turbines, an estimate of the heat input is often used. If actual data for the primary production of nuclear energy is available, this is used in the energy balance. However, due to lack of data, primary production of nuclear energy is often calculated on basis of the electricity production of nuclear energy with an average thermal efficiency of 33 per cent. This means that the primary production (heat equivalent) is estimated to be three times higher than the actual electricity production. If the nuclear electricity production for instance is 50 TWh, the primary nuclear production becomes $50/0.33 = 152$ TWh. The difference between the actual production and the estimated primary production are estimated losses. For geothermal energy, the thermal efficiency is assumed to be about 10 per cent only, which imply 90 % estimated losses. See IEA/OECD 2004 for more information.

As we can see there are challenges with both methods and the sum of primary energy production are for some countries partly based on estimated figures.

1.7 Manuals

The UN has, in cooperation with the Oslo Group on Energy Statistics and the InterEnerstat², in the last years been writing a draft manual on energy statistics, in order to harmonise energy definitions, methodologies and conversion factors among countries and organizations. In addition, the IEA is working on a manual on energy indicators. These manual will hopefully lead to a better harmonization of definitions and methodologies and quality in the countries energy statistics, but there will remain many challenges. Even if certain methodologies are recommended in the manuals, it is costly and time demanding for the countries to introduce new methods, because it means that they have to revise energy statistic many years back in time in order to obtain comparable time series.

1.8 Losses of energy

When energy is converted or consumed for end-use, some of the potential energy content is lost due to friction, heat loss or other factors. (In this context, differences between gross and net calorific values, mentioned in the previous section about definition and conversion factors, are not considered as losses). The energy that is utilised is less than the energy supplied, which we originally purchased. Knowledge about the utilised energy, and for which devices and energy commodities the energy losses are the greatest, constitutes very useful information for many reasons. It could, for instance, explain how a switch from one energy commodity to another influences the trend in energy consumption. As an example, a switch from burning wood to using electric space heating implies that the energy supply requirement is reduced since electrical heaters are more efficient than wood stoves. For energy planning and analytical purposes, information about losses and useful energy gives a broader perspective on energy consumption and its harmful consequences than figures for supplied energy consumption alone. Such a perspective might indicate whether switching to more efficient fuels could be an appropriate way to save energy, or if investments in more efficient equipment are the way to go. Nevertheless, most statistics are only presented as supplied energy, not as utilised energy.

Losses of energy appear from the following processes and activities

- There are losses in transformation to derived energy, depending on the efficiency of the plants that transform the energy. For instance when converting heat from waste combustion or biofuels to district heating in district heat plants, much of the potential energy is lost.
- Transport of electricity through a grid network involves losses due to friction and the transport process itself. The longer the grid, the larger electricity loss.
- When energy is used for end-purposes, e.g. in stoves, engines etc., some of the potential energy will be lost due to friction and inefficiencies in the equipment. The losses vary widely among different energy sources and devices. The energy efficiency in combustion engines is only about 20-30 per cent, which means that 70-80 per cent of the potential energy in transport fuels are not utilised. In fuel wood stoves, the efficiency is assumed to be about 65 per cent.

The degree of utilization of the individual energy commodities will also depend on the device and technology available where it is used, and the technology changes over time. For instance, new wood stoves are usually more efficient than old ones. Usually, you consider electricity to have an utilisation degree of 100 per cent (when you disregard losses in distribution of electricity). However, this could depend on how you define the efficiency. For instance, an electric light bulb might have 5% efficiency in emitting light, while the remaining 95 per cent of the energy is heating the room. This means that the

² The InterEnerstat is a group of organisations where an important objective is to harmonise methodologies and definitions in energy data collection and energy statistics

wanted effect is 5 per cent while the total effect is 100 per cent. Due to the way electricity is measured (in kWh), output equals input (1 kWh in = 1 kWh out), but there is a question whether the coefficient for light bulbs should be 5 or 100 per cent.

1.9 Risk of carbon leakage and challenges related to transport

EUs quota directive set a limit for total emissions in EU countries, while the renewable energy directive imposes EU to increase their renewable energy share from 8.5 per cent in 2005 to 20 per cent in 2020. There are many possible ways to reduce emissions and increase the use of renewable energy, such as replacing fossil fuels with renewable energy, carbon capture and storage plants, energy saving efforts. Incentives to promote this kind of behaviour are for instance different kind of regulations or increased taxes on energy or emissions which make energy intensive and pollutive manufacturing less profitable. This might again lead to shutting down of these kinds of industries or less new establishments. However, this does not necessarily mean that the world becomes less dependent on energy intensive products. One consequence could be that these products to larger degree will be produced in developing countries sometimes with less efficient technology and less environmental friendly energy consumption such as coal, but with cheaper labour force and less taxes and regulations so they still have a trading advantage. If production moves offshore to a cheaper country with lower standards, global emissions will not be reduced. It could instead be increased. We have seen that China has had an enormous economic growth, which has contributed to a significant increase in energy demand, and it is likely that this is partly related to their massive export of cheap commodities to developed countries. Imports and exports of commodities are energy intensive in themselves, due to the considerable energy needs of flights, ships, lorries etc. However, it is economically advantageous to import products that are produced cheaper abroad and to export products that your country can produce in a competitive way. Cheap transport costs make it even more economic to behave in this manner.

It is important to think in a global perspective when trying to fulfil targets and directives for reduced fossil fuel consumption and emissions. Efforts that effectively reduce energy consumption on a national basis might in worst case have negative consequences on a global basis. But it is difficult to take into account this kind of effects because the developed countries mainly have targets for their own emissions and energy consumption. Developing countries do still not have any fixed targets for emission reductions. However, developed countries can invest in efforts that reduce emissions in undeveloped countries through the Clean Development Mechanism and by that improve the situation in undeveloped countries.

One of the largest challenges we have in front of us, is to limit the growth in energy consumption for transport. Energy consumption in transport is mainly based on fossil fuels, and on it is difficult to replace it with renewable energy sources, at least on a short run. Transport makes up a significant and increasing share of the world's energy consumption. About 27-28 per cent of the world's final domestic consumption has been used for transport purposes since 2000. The corresponding share in 1970 was 23 per cent. In addition we have international aviation and navigation, which also have increased considerably, and which corresponds to about 4 per cent of the world's total domestic consumption of energy. (source IEA)

1.10 Energy indicators

It is not an easy task to compile energy statistics and energy indicators which give a representative and clear picture of the energy situation. For users of statistics, it can be difficult to interpret aggregated energy indicators without going beyond the data and see it in coherence with the industry structure and demographic situation in the country. A high dependency rate (many children and retired persons) could for instance explain a low

GDP / capita in a country. Sometimes we need several kinds of indicators that illustrate different aspects in energy statistics.

An aggregated energy indicator showing energy consumption per GDP for the country is not very helpful if you do not know anything about the figures beyond these indicators. Many countries change their industry structure over time in favour of less energy intensive service sectors at the expense of energy intensive manufacturing industries. In this case, a drop in energy per unit GDP does not only reflect a more energy efficient society, but also a structural change.

To illustrate that traditional energy indicators not gives an unambiguous picture of changes in the energy efficiency, I will present a few examples from Norway. Figure 1 shows the development in energy consumption / unit GDP in Norway for the period 1990 to 2008. This energy intensity has declined by 21 per cent and one could believe that this is only due to improved energy efficiency. However, when looking closer at the data beyond the graph, we can see that some of the development could be attributed to structural changes. The manufacturing industries share of the total value added has dropped by around 4 percentage points, and their share of the labour stock has declined by 1.4 percentage points from 1990 to 2008. Services, which are less energy intensive has, on the other hand, increased its share of the value added by about 4 per cent, while their share of the labour force rose by 5 per cent in the same period.

On average, the energy intensity in manufacturing industries is around 800 MWh/million NOK, while around 50-60 MWh / million NOK (Norwegian Kroner) in the service sector. Table 1 shows some examples of the energy intensity in different industries. We can see that it varies considerably between services and certain energy intensive manufacturing industries, from more than 5000 MWh/mill NOK for basic chemicals to 40 MWh/mill NOK for health services. It is obvious that a change in the industry structure will affect the overall energy intensity in the economy. When looking at the development in energy intensity in different sectors, we get a more nuanced picture compared to what we get when we study the average for the whole economy. We can observe that the energy intensity has increased in some sectors and dropped in others in the period. From figure 2 we can also see that value added per man hour by sector, and oil industry stands out as the most profitable, while the profitability in other sectors are more equal in spite of large variations in the energy intensity.

Figure 1. Development in energy intensities and labour productivity in Norway, 1990-2008.

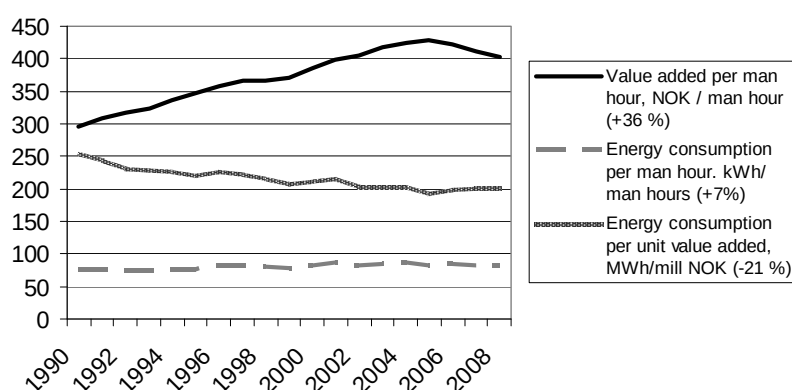


Table 1. Energy intensities and value added /man hour in certain industries in Norway. 2008

	MWh energy / value added in mill. NOK	Value added (NOK) / man hour	Energy (kWh)/ man hour
Wood and wood products	1 748	638	1 115
Air transport	1 516	396	601
Basic metals	3 690	526	1 940
Basic chemicals	5 259	461	2 424

Education, local gov	43	254	11
Health services, local gov	19	216	4
Oil and gas extraction	195	7 173	1 400

As seen from figure 1, the value added per man hour, also called labour productivity, has increased considerably, with 36 % from 1990 to 2008. Changes in the productivity can depend on market conditions and trends, because the enterprises cannot adjust their capital and labour force at the same pace as the variations in sale and production. This does not have anything to do with changes in energy efficiency. Increased labour productivity could also be due to that each employee is equipped with more real capital or intermediate goods. Furthermore, it could be a result of technological development, meaning the improved ability to utilise a given quantity of input due to more knowledge or innovations. Energy consumption belongs to the category of intermediate goods, and energy consumption per man hour has increased by 7 per cent in this period, which is much less than the increase in the productivity. If a given input of energy gives higher value added due to more energy efficient equipment, this could be interpreted as improved energy efficiency. However, there are so many other factors that also influence the total value added, so we cannot say that changes in energy consumption per unit of value added only reflect changes in the energy efficiency.

1.12 Summary

We have seen that there are many uncertainties in statistics, and it is important to be critical to what kind of data we use to illustrate different kind of problems. There are also many aspects that are not covered by energy statistics. The production of biofuels and biomass imply land use change, which could have been utilised for other purposes. Production of fossil fuels implies depletion of coal, gas and oil resources. All production of energy requires a lot of capital and labour. Moreover, there are the harmful emissions that are generated as a result of extraction, conversion and consumption of energy. All these additional costs are not very visible in basic energy statistics, or in the energy balance. It is necessary to combine several kinds of statistics in order to get an overall and complete picture of the effects of production and use of energy. Still statistics is an essential tool for all kinds of energy policies and analyses. Statistics show us for instance that it is necessary to give special attention to the fast increasing transport sector. It is also important to think in a global perspective when trying to reduce emissions and fossil fuel use, as certain efforts can increase the risk of carbon leakage.

REFERENCES

Energy Statistics Manual OECD/IEA 2004

World Energy balances, IEA.

Bjart Holtsmark (2010): "About woodcutting and Climate Neutrality", *Economic analyses* no. 3/2010, Statistics Norway

FROM BALANCES TO ACCOUNTS: A MEANINGFUL REORGANISATION OF ENERGY DATA

Giusy Vetrella, Aldo Femia**

Italian National Institute of Statistics (Istat), National Accounts, Environmental Accounts

ABSTRACT

Istat currently produces, for the purposes of environmental accounts, a three-dimensional Energy Use Table (EUT) in physical units broken down by energy product, activity and purpose. The energy product split of the table is consistent with the Eurostat energy product classification. Energy-users – comprising producers of (energy and non-energy) goods and services, as well as final consumers (households) – are classified according to national accounts classifications; in particular the NACE – the statistical classification of economic activities in the European Community – is used for production activities. Finally, the split by purpose includes “energy use with combustion” (specifically “road transport”, “off road transport”, “heating”, “transformation in electricity” and “other energy use with combustion”), “energy use without combustion” and “non-energy use”. The current Istat EUT has been developed, drawing from earlier experience, for use in the framework of the construction of Air Emission Accounts in order to distribute the emissions of certain combustion-related processes, mainly heating and transport, among the economic agents that directly cause the emissions. Indeed, no ready-available data source on energy use can by itself serve this purpose. The main energy data sources, from which the Istat EUT is derived are the physical energy use table by activity and energy product (not by purpose), produced at Istat as a basis for the national accounts’ monetary supply and use table, and the National Energy Balance; other minor sources of information are also used. By appropriately combining all sources together, preliminary estimates of the three-dimensional split of energy uses can be obtained, while final estimates must be derived by means of a statistical balancing method that allows to distribute optimally the statistical discrepancies between the different sources. The three-dimensional split of the table makes it suitable, besides for distributing air emissions, for different uses. In particular, it allows analyses that are scientifically sound, thanks to the split by purpose and energy product, and policy relevant at the same time, since the split by activity allows energy use data to dialogue with economic data, i.e. to take appropriately into account the economic dimension.

Keywords: Energy Use, Energy Balance, Energy Accounts, Air Emission Accounts, Namea

1. INTRODUCTION

Within the framework of the System of National Accounts (SNA), Istat develops Satellite Accounts, aiming at complementing the core of the System, which analyses e.g. production and value added, by introducing new concepts and information, but without disrupting it. The new information concerns, among other things, the physical aspect of economic phenomena, which is relevant with respect to the ecological sustainability of development, and in particular to issues such as resource scarcity and pressure on the natural environment. This is done in a way that enables the users of the Accounts to put the physical phenomena in a meaningful relation with the traditional monetary aggregates. The keyword for Satellite Accounts is “integration” with core National Accounts, which is to be understood in terms both of use (to the extent possible) of the same concepts and

(*) Giusy Vetrella - +39 06 4673 7578 – vetrella@istat.it
Aldo Femia - +39 06 4673 7572 – femia@istat.it

The paper is the result of joint work of two authors. The paragraphs were authored as follows: §§ 3 and 4. by Giusy Vetrella; §§ 1,2,5 by Aldo Femia.

classifications and of production processes of statistical information, but not in modification of the definitions of the core aggregates, which would otherwise lose their current meaning without necessarily gaining a clear new meaning.

A very important and rapidly developing piece of this work is that of the construction of Energy and Air Emission Accounts, which are tightly bound together for obvious reasons (e.g. more than 80% of greenhouse gas emissions derive from the use of fuels).

The present paper focuses on the Energy Use Tables (EUTs) developed at Istat through time. We first briefly mention the reasons why the National Energy Balance (NEB) is not a sufficient source of information for Energy and Air Emission Accounts (§2), then we discuss the evolution of the Istat Energy Use Table (§3), whose current characteristics we illustrate (§4) before summing up and drawing some general conclusions (§5).

2. SHORTCOMINGS AND POSSIBILITIES OF USE OF THE NATIONAL ENERGY BALANCE FOR ENERGY AND AIR EMISSION ACCOUNTS

The NEB, published annually in Italy by the Ministry of Industry (using a slightly different format from that proposed by Eurostat) is a regular and comprehensive source of data on energy consumption, concerning the use of around 30 different energy products.

One problem with the NEB is the lack of sufficient metadata, i.e. a thorough description of the way the figures are compiled. However, its most important limit as a general source of data for Energy and Air Emission Accounts is the inadequacy of the disaggregation of energy uses by activity. In the Satellite Accounts context, “activity” includes both *production activity* (production of goods and services classified by industry, according to the NACE - the statistical classification of economic activities in the European Community) and *households consumption activity* (use of products purchased by final users).

The following are examples of this shortcoming:

- the consumption of energy products for transport is broken down by type of transport (road, rail, maritime, air) and not by activity;
- the consumption of energy products for industrial production processes is broken down by industrial sector but the classification used and the units classified are not in a clear correspondence to National Accounting concepts; in particular, the classification of production activities is not the NACE.

The lack or insufficiency of the detail provided by the NEB on the activities using energy products is a very serious shortcoming for the purposes of Satellite Accounts, as it does not allow the user to connect the physical data on energy consumption to the data on production, value added, employment, etc, at a level fit for economically meaningful and policy-relevant analysis.

Moreover, the NEB does not respect the “residence principle”. Nevertheless its totals provide important information, since they are otherwise consistent with National Accounting definitions. Before using them for Energy and Air Emission Accounts, therefore, it is both necessary and sufficient to “correct” them by e.g. the energy used by foreign units engaged in international travel leaving from the Italian national territory¹.

Besides these totals, the most valuable pieces of information provided by the NEB for the purpose of constructing Energy and Air Emission Accounts is the identification of different functions for which the individual energy products may be used. In paragraph 3.4 we illustrate the details in this respect.

Finally, NEB data can in some cases be used as a direct source of information (e.g. for some energy products in the case of the off-road transport) or as a check for estimates

¹ An institutional unit is said to be resident within the economic territory of a country when it maintains a centre of economic interest in that territory - that is, when it engages, or intends to engage, in economic activities or transactions on a significant scale either indefinitely or over a long period of time, usually interpreted as one year. Some of the production of a resident institutional unit may take place abroad, while some of the production taking place within a country may be attributable to foreign institutional units.

obtained from other sources since some equalities or inequalities (“greater than”, “smaller than” relations) must hold between certain figures in the NEB and the aggregates to be included in Energy Use Tables.

3. DEVELOPMENT OF THE ISTAT ENERGY USE TABLES

Given the inadequacy of the ready-available data sources for the physical Satellite Accounts, in 1999 Istat began to develop an *ad hoc* EUT. Initially this was done for the internal purpose of distributing some energy-related air emissions to the activities that cause them, but later, as the utility of well-organised data was proven by analytical applications, Energy Accounts became an autonomous objective in the framework of Satellite Accounting and refinement of the results was put on the agenda. In the following we describe the development of the Istat EUTs, starting with the oldest experience.

3.1. The 1975, 1980, 1982 and 1988 Istat Energy Use Table

Tables on energy uses in physical terms by activity and purpose had been produced and published by Istat before the 1990ies, generally in connection with the construction and publication of the Input/Output Table², whose data on the transactions of some energy products are obtained by the “price x quantities” method. These Tables had 1975, 1980, 1982 and 1988 as reference years. The Tables provide data on the use of 25 energy products by 92 production activities (classified by the Italian version of NACE70) plus private consumption. For each product, the total amount used was broken down by purpose or type of use (“transport”, “heating”, “non-energy use” and “other use”; see table 1) and by origin of supply (“domestic production” and “imports”). Data are available in four units: metric units; tonnes of oil equivalent (toe); market price; depart-usine price.

It must be noticed that the use purposes were not always very well identified by the names given to them. This is the case especially for “non-energy uses”, that comprised the transformation of energy products into other energy products, including the generation of electricity from burning fuels.

Table 1. Purposes of energy use in the 1975, 1980, 1982 and 1988 Istat Energy Use Tables includes:

PURPOSES	PRODUCTION ACTIVITIES	HOUSEHOLDS
Heating use	heating (office building, factory, ...); use of electricity for heating	heating (home); use of electricity for heating
Transport use	road transport carried out both as principal and secondary activity and as ancillary activity (own account); railway, air and maritime transport as well as all operations of ships, boats; use of electricity for transport	road transport by households (own account); off-road transport by household (mainly operations of boats); use of electricity for transport
Other energy use	energy products used in production processes (excluding heating, transport and transformation); use of electricity (excluding heating and transport)	energy products used in cooking and for hot water; use of electricity (excluding heating and transport)
Non-energy use	all kind of transformation, i.e. energy products used to produce other products (energy and non-energy products); energy products used for non energy purposes (degreasing, dry cleaning, ...)	energy products used for non energy purposes (degreasing, lubrication, ...)

² For details on the methodology of the Istat Energy Use Tables see Istat (1981), Istat (1988a), Istat (1988b) and Istat (1991).

3.2. Use of the 1988 Energy Use Table

The 1988 Energy Use Tables were used for the first Air Emission Account of Italy, set up in 1999 with 1990 as reference year.

Official air emission data compiled by the Italian environment protection agency (now ISPRA) according to the CORINAIR system, follow a classification of technical “processes” that cause air pollution, the Selected Nomenclature for sources of Air Pollution (SNAP). Despite the names of some of its “sectors”, this classification is not directly related to that of activities used in the National Accounts. As a consequence, some processes which are very important in terms of air emissions take place in many different activities. Therefore in order to distribute the emissions of these processes across activities it was necessary to identify and use suitable indicators. Energy use is a natural candidate, especially for processes that imply combustion, such as heating and transport processes, which are also those that are common to most activities. To correctly use the Energy Use Tables and make the most of the information contained in it, however, it is first of all necessary to thoroughly check two correspondences:

- that between EUTs products and CORINAIR energy products³, and
- that between EUTs “purposes” and the CORINAIR processes whose emissions had to be distributed.

The existence of these correspondences is a minimum pre-requisite for considering the information on the percentage distribution by activity of the energy consumed for a given purpose, as valuable information about the percentage distribution by activity of the emissions of the processes corresponding to that purpose. The tighter the correspondence, the better the approximation. The analysis showed the following main results:

- the purpose “heating” of the Table was consistent with the SNAP processes related to heating (processes of the source category 02 in the CORINAIR inventory);
- the purpose “transport” of the Table corresponded to the SNAP processes related to road transport (07), railways (0802), inland waterways (0803), maritime activities (0804), airports (0805). Only one “transport” process that needed to be distributed among several production activities, namely “off-road industry” (0808), did not find a clear match with this table’s purpose, and its emissions had to be distributed by a different method;
- the purpose “other energy use” of the Table was consistent with the SNAP processes related to combustion for purposes other than heating and transport (processes of source categories 01 and 03 in the CORINAIR inventory);
- the purpose “non-energy use” of the Table did not relate to any of the CORINAIR processes whose emissions needed to be distributed.

Summing up, the results of the check allowed to conclude that the 1988 Energy Use Table could be used as a tool for distributing the emissions of most of the processes that needed it, on the basis of the correspondence found between the purposes of the Table and the processes.

3.3. The 1992 Istat Energy Use Table

In 2001 new Air Emission Accounts, referred to 1991 and 1992, were constructed. On this occasion, the possibilities of use of a new Energy Table, which had been developed in the meantime, containing data referring to 1992, was investigated⁴. As for the previous Tables, the 1992 Table had been produced for the compilation of the energy

³ CORINAIR energy products follow the NAPFUE classification whereas the Istat energy products are consistent with the Eurostat energy product classification.

⁴ See Giansante (2000).

sector of the I/O Tables but differed both for the methodology applied to build it and in its structure, as it provided input to completely revised National Accounts. It contained data on the use of 29 energy products used by 101 production activities classified according to the Italian version of NACE Rev.1 and by households.

Unfortunately the 1992 Energy Tables was not provided in the breakdown by purpose; only the data on the consumption of the main energy products by households was available already in a split highlighting two main purposes: transport and other (mainly heating).

Since the split by purpose plays indeed an important role in the allocation of emissions in the Air Emission Accounts, alternative solutions were sought in order to compensate for the lack of data by purpose. The solution adopted was to apply the split by purpose of each activity of the 1988 data to the total use by activity of the 1992 data. In order to make this split it was also considered that the 1992 Energy Table includes, in total energy consumption by activity, some components that were excluded from 1988 Energy Use Table, namely transport in military, agriculture, forestry, industry and gardening activities. Accordingly, the "transport use" of the 1992 Istat EUT is divided in two parts ("road transport use" and "off-road transport use"), which include the items described in table 2.

Table 2. "Transport use" purpose used in the 1992 Istat Energy Use Tables (produced in 2001)

PURPOSES		includes:	
		PRODUCTION ACTIVITIES	HOUSEHOLDS
Transport use	Road transport use	road transport carried out both as principal and secondary activity and as ancillary activity (own account); use of electricity for road transport	road transport by households (own account); use of electricity for road transport
	Off-road transport use	railway, air and maritime transport as well as all operations of ships, boats, tractors, construction machinery, lawn mowers, military and other equipment; use of electricity for off-road transport	off-road transport by household (mainly operations of boats and lawn mowers); use of electricity for off-road transport

3.4. The 1999 Istat Energy Use Table

In 2003 Istat developed the Air Emission Accounts with reference to 1999. Again, the data source to split the emissions of the CORINAIR combustion-related processes between the related activities was found in the National Accounting data on energy use by activity. Again, the split by function was originally not available in these data. The reference year, moreover, was too far away from 1988 for using that year's structure. Therefore an *ad hoc* working group was set up in order to devise a specific method for the split by purpose. The method developed is based on the following main steps:

1. identification of five different purposes - road transport, off-road transport, heating, other energy use, non-energy use (see tables 1 and 2) - within the NEB (see table 3); basic inputs to this calculation included information from CORINAIR experts on which NEB sections are used to estimate specific CORINAIR emissions as well as qualitative information on the contents of the uses in previous Istat Energy Use Tables;
2. assessment of the link between Istat energy products and NEB energy products;
3. calculation, for each Istat energy product, of the share of the five different uses based on NEB data.

Table 3. Correspondence between Italian NEB data and purposes for the 1999 EUT (produced in 2003)

Structure of the Italian NEB	Energy products	Use purpose
Bunker	all	Off-road transport use
Transformations of energy sources	all	Non-energy use
Consumption and losses in the energy sector	all	Other energy use
Final energy consumption:		
- Agriculture and fishing	fuel oil, kerosene	Heating use
	motor gasoline, diesel oil	Off-road transport use
	natural gas, LPG, electricity	Other energy use
- Industry	diesel oil**, jet fuel	Off-road transport use
	LPG**, diesel oil**, fuel oil**	Road transport
	all (except jet fuel and shares of LPG, diesel oil, fuel oil)	Other energy use
- Services:		
Rail transport	all	Off-road transport use
Navigation	all	Off-road transport use
Road transport	all	Road transport use
Air transport	all	Off-road transport use
Other public services	electricity	Other energy use
Public administration	fuel oil, LPG*, diesel oil*	Heating use
	jet fuel, motor gasoline, diesel oil**	Off-road transport use
	LPG*, diesel oil***	Road transport use
	electricity	Other energy use
- Households, commerce and handicrafts	LPG**, natural gas**	Other energy use
	all (except shares of LPG, natural gas)	Heating use
- Non-energy use	all	Non-energy use

* only the share indicated in the NEB footnotes; ** only a share, indicated in another source; *** only the share indicated in the NEB footnotes less the share for off-road transport, indicated in another source

3.5. The 1990-2000 Energy Use Tables

In 2004 the method developed in 2003 was applied to produce EUTs by energy product, activity and purpose from 1990 to 2000. The method was slightly revised, with the main new development being the implementation of a balancing procedure, similar to that used for monetary national accounts, devised to distribute the discrepancies and uncertainties of the data in an optimal way between the cells of the three-dimensional matrices.

In practice, in order to obtain the Istat EUTs, the starting point is, for each energy product:

- intermediate consumption by production activity (101) and households' final consumption - 102x1 column vector (*ex ante* estimate of the EUT column marginal values);
- total (final and intermediate) consumption by purpose (road transport, off road transport, heating, other energy use, non-energy use) - 1x5 row vector (*ex ante* estimate of the EUT row marginal values), obtained by breaking down by purpose the total consumption (the sum of the 102 components of the vector under point "a"), mainly on the basis of NEB data;
- ex ante* estimates (based on *prior* knowledge and hypothesis) on energy use by activity and function - 102x5 matrix;
- variances of the *ex ante* estimates - 103x6 matrix (including the marginal column and row values); the matrix values, ranging between 0 and 1, represent the relative degree of reliability of the individual *ex ante* estimates;
- set of constraints (row totals equal to the corresponding marginal column values; column totals equal to the corresponding marginal row values; the marginal row total as well as the marginal column total equal to the general total of the *ex ante*

estimates matrix; constrains that apply to parts of the matrix of the *ex ante* estimates).

Data under “a”, “b” and “c” above are independently estimated; hence, they are not balanced, i.e. they do not satisfy the constrains under “e”.

After building the *ex ante* estimates and defining the constrains and variances, the final data within the EUT matrix are obtained in two steps:

1. analysis of the residuals of the non-balanced equation system; if the residuals generated by the independent *ex ante* estimates are very high, the second stage of the method (described below) may lead to non significant results.
2. balancing; the balancing method, commonly applied to national accounts data, consists in redistributing the discrepancies among the *ex ante* estimates by means of prior information on the accuracy of the individual estimates (variances under point “d” above): the less the accuracy, the bigger the value change deriving from the redistribution of the residuals. The degree of accuracy in the *ex ante* estimates is assessed, in turn, on the basis of the quality and completeness of statistical sources as well as of the features of the estimation method.

4. THE CURRENT ISTAT ENERGY USE TABLES

Istat currently produces a 3-D EUT for each year, in physical units, describing the energy consumption by energy product, activity and purpose, following the method developed in 2004, but for the purposes in which the energy consumption is broken down, which have been radically innovated with respect to those reported in tables 1 and 2.

The *purposes* of the current EUT are described in Table 4. They are identified according to the following logic: first “non-energy use” (e.g. transformation of oil into plastics) is singled out; second, among the energy uses, the “energy use without combustion” (e.g. transformation of oil into motor gasoline) is isolated from the uses that imply combustion; finally the processes implying combustion are further specified according to the nature of the use, so that “heating”, “road transport”, “off road transport”, “transformation in electricity” and “other energy uses with combustion” are identified.

Table 4. Purposes used in the current Istat Energy Use Tables

PURPOSES	includes:	
	PRODUCTION ACTIVITIES	HOUSEHOLDS
Energy use with combustion	Heating use	heating (office building, factory, ...)
	Road transport use	heating (home)
	Off-road transport use	road transport carried out both as principal and secondary activity and as ancillary activity (own account)
	Transformation in electricity	road transport by households (own account)
	Other energy use with combustion	off-road transport by household (mainly operations of boats and lawn mowers)
Energy use without combustion	energy products used to produce electricity (transformation in electricity)	
	energy products used in production processes (excluding heating, transport and transformation)	
Non-energy use	energy products used to produce other energy products (transformation in energy products different from electricity); use of electricity for all purposes	
	energy products used to produce non-energy products (transformation in non-energy products); energy products used for non energy purposes (degreasing, dry cleaning, ...)	
		energy products used in cooking and for hot water
		use of electricity for all purposes
		energy products used for non energy purposes (degreasing, lubrication, ...)

Activities include households and production activities; the latter are classified according to the current version of the NACE.

Energy products are classified consistently with the Eurostat energy product classification. The energy products' list is quite complete, as it includes 27 products (coal, lignite, peat, natural gas, crude oil, waste, electricity, coke, coke oven gas, non-energy coal products, gas work gas, blast furnace gas, LPG, refinery gas, naphta, motor gasoline, aviation gasoline, jet fuel, kerosene, diesel oil, fuel oil, petroleum coke, white spirit, bitumen, lubricants, chemical products, ETBE). In the EUT each product is expressed in its own metric unit, so that aggregation across products is possible only after transformation in a common unit.

Istat EUTs will soon be published (without the split by product) for the years 1990-2008.

5. SUMMARY AND CONCLUSIONS

The construction of the EUTs at Istat is embedded in the process of construction of the National Economic Accounts for energy products, as well as of Physical Satellite Environmental Accounts. In particular, given a energetic product, the total consumption by activity stems from the production process of traditional National Economic Accounts, as a piece of information necessary to evaluate the quantities used by each industry by the "price times quantity" method. This part of the process uses information coming from several different sources and guarantees coherence with all other national accounting aggregates. The latter condition is essential for any analytical application bearing on the correspondence between economic values (output, value added, etc.) and physical quantities. This holds also for physical quantities other than energy products themselves, but which are related to energy use, as is the case for air emissions. This leads us to the second part of the construction process of the EUTs, the split by purpose (or type of use) of the total amounts of the energy products used by each industry. This split is in fact necessary in the context of the construction of the Air Emission Accounts in order to distribute among activities the emissions deriving from processes which are carried out in industries as well as in final uses of households. Indeed, the basic air emission data are available according to the atmospheric emission CORINAIR inventory which is based on a classification of technical processes (SNAP - Selected Nomenclature for sources of Air Pollution). In this classification, some very important categories of polluting processes (such as heating and transportation) are orthogonal to the activities, i.e. they take place in several households and production activities. However, for analytical purposes, it is the latter classification that is most meaningful, as physical data on energy consumption or air emissions can be compared to economic data (value added, output, employment, intermediate consumption, tax revenues and so forth) only when they are given according to the NACE.

The joint use of the classifications by product and purpose makes sure that no individual cell of the EUT may be affected by double counting, i.e. that the same energy that is embodied in different products at different stages. Clearly, this is not the case when all cells or certain groups of cells are considered together: aggregation across the dimensions of the EUT should be made with great care, paying attention to the possibility of counting twice the same energy.

Of course, a three dimensional set of data can be seen as a collection of several bi-dimensional Tables. Depending on the way the EUT is looked at, it may be seen:

- as a set of Tables by activity and purpose, each referring to a single product. In this case all the data in any individual bi-dimensional Table are in the same measurement unit and the figures may be summed up by row and/or by column without any need for transformation; the figures resulting from these possible aggregations are not affected by double counting, as no individual product may be used twice, as all kinds of uses imply physical transformation in something else (air emissions, other energy products appearing in different tables, dispersed heat). In

order to add-up all these Tables together, transformation is needed. If certain partial tables are summed up together, double counting appears.

- as a set of Tables by product and activity, each referring to a single purpose. In this case there are several measurement units in any single table and aggregation may be possible only after transformation. Double counting is present only in the table for “Energy use without combustion”, as it is here that products may appear both before and after transformation.
- as a set of Tables by product and purpose, each of which referring to a single activity. Also in this case there are several units.

The three-dimensional split of the table makes it suitable for many different uses. At Istat it is used for distributing air emissions, as widely documented in this paper, but not only for that. For instance, analytical applications concerning the relationship between energy intensity and emission intensity of the economic activities have been performed, with interesting outcomes also in a policy perspective.

In conclusion, the 3-D Istat EUT allows analyses that are scientifically sound, thanks to the split by use purpose and fuel, and policy relevant at the same time, since the split by activity allows energy use data to dialogue with economic data, i.e. to take appropriately into account the economic dimension.

REFERENCES

- Agresti A.M., Moauro F. (1997), *Problemi di trascodifica nel sistema di Contabilità Nazionale* in Documenti Istat n.15/1997, Istat
- ENEA (1995), CORINAIR project, *Air pollutant emission inventory in Italy for the year 1990*, Final report
- Eurostat (1996), *European System of Accounts. ESA 1995*, Luxembourg
- Eurostat (1998), *NOSE Manual*, Luxembourg
- Eurostat (1999), *Pilot studies on NAMEAs for air emissions with a comparison at European level*, Eurostat, Luxembourg
- Giansante C. (2000), *Gli impieghi di energia nella tavola I/O 1992: aspetti metodologici*, Documenti Istat n.1/2000, Istat
- Istat (1981), *Gli impieghi di energia in Italia nel 1975*, Supplemento al Bollettino mensile di statistica, Anno 1981 n. 6, Istat
- Istat (1988a), *Gli impieghi dell'energia in Italia nel 1982*, Collana d'informazione, edizione 1988 n. 17, Istat
- Istat (1988b), *Tavola degli impieghi energetici* (floppy disk).
- Istat (1991), *Gli impieghi dell'energia in Italia nel 1985*, Collana d'informazione, edizione 1991 n. 2, Istat
- Istat (2009), *Contabilità ambientale e pressioni sull'ambiente naturale: dagli schemi alle realizzazioni*, Annali di Statistica n. 2, Istat
- Ministero dell'Industria, *Bilancio Energetico Nazionale (several years)*
- Nicolardi V. (2000), *Balancing large accounting systems: an application to the 1992 Italian I-O Table*, Proceedings of the “XIII International Conference on Input-Output Techniques”, University of Macerata, Italy, August 21-25th, 2000
- Stahl H. (1998), *EPIS - Air emissions - Corinair Conversion System*, Öko-Institut e.V., Darmstadt - Final Version, 19.11.1998
- United Nations et al. (1993), *System of National Accounts 1993*, New York

CONCLUDING SESSION
WHERE DO WE GO FROM HERE?

Tverberg G. E.

PEAK OIL AND THE CONTINUING FINANCIAL CRISIS

PEAK OIL AND THE CONTINUING FINANCIAL CRISIS

Gail E. Tverberg*

FCAS, MAAA

ABSTRACT

Regardless of what governments tell us, the financial crisis is not over. The leveling of oil production has been a major contributor to the recent financial crisis. Going forward, we can expect more disruption, since oil supply, net of the energy used in production, is already contracting. One of the big issues is that the size of the economy will almost certainly contract, as oil and other resources contract. This has profound impacts. Debt becomes much more difficult to repay in a declining economy. This causes financial institutions including banks, insurance companies, and pension funds to have financial problems.

Government entitlement programs, as for the aging, also become much more difficult to fund. Governments, because of both debt problems and problems with entitlement programs, can be expected to have increasing financial problems, with some defaulting.

Debt has ramped up greatly since 1970. This growth in debt has helped boost spending and demand. But with more debt defaults, we can expect the reverse of this: a huge decline in debt, leading to reduced spending and reduced demand.

Going forward, it is quite possible we will encounter a scenario not too different from some of the more adverse scenarios of the "Limits to Growth" analysis of the 1970s. Governmental and other defaults may lead to reduced international trade. The benefits of globalization may eventually be lost, including the ability to make high tech goods.

Today, I would like to talk to you about the connection between peak oil and the financial crisis—or really the continuing financial crisis.

Comparison Between Growing and Declining Economy

We are hearing from our governments that the recession is over. But I think what is happening is a very major change, as we shift from a growth economy to a declining economy. We can envision a growth economy as a series of larger and larger disks, with each disk representing the amount of goods and services that can be made with the resources available at a given point and time.

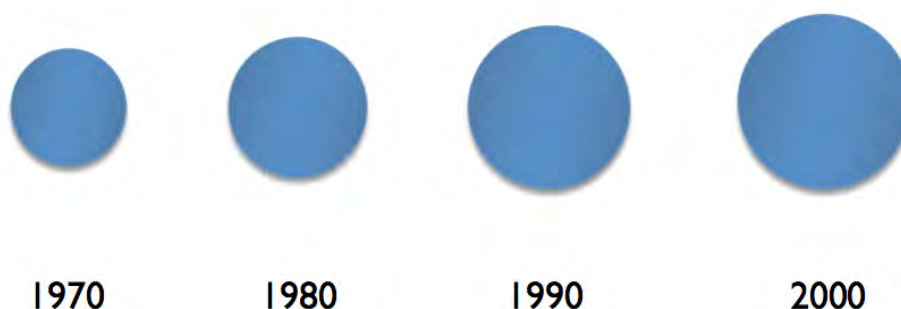


Figure 1. Representation of a Growing Economy

As the economy grows in real terms, so does the amount of goods and services available for each person. We all have to share in the output at a given point in time, but

* E-mail: GailTverberg@comcast.net

as long as it is growing, it is fairly easy to have enough for everyone—workers, retirees, stockholders, bondholders, and those planning to invest in new energy infrastructure, to name a few.

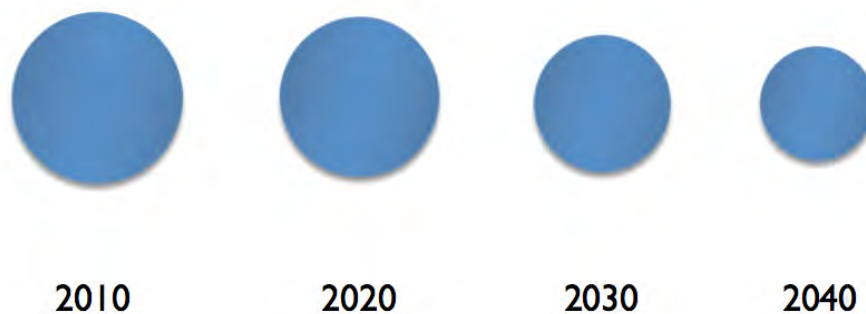


Figure 2. Representation of a Declining Economy

But going forward, we know that the amount of oil is likely to be declining. In fact, if we think of oil on a net basis—net of the oil used to produce and distribute the oil, the quantity of oil available is probably already declining, since the total amount of oil produced each year has been flat since 2005, and the amount of oil required for extraction of oil likely has been increasing, as oil from more difficult locations is accessed.

As the net amount of oil that is produced each year decreases, the amount of goods and services that we can produce with that oil is likely to decline as well, although perhaps not at exactly the same rate as the oil decline. Somehow, all of those needing goods and services will need to share in whatever size circle is available at a given point in time.

Overview of Presentation

Where does a declining oil supply lead us? I see several implications:

1. Oil shortages lead to **economic** decline – what we think of as recession
2. Economic decline leads to **lots** of debt defaults
3. **Lots** of debt defaults leads to a **troubled** financial system
4. Governments are also likely to get into financial difficulty, and some may default on their debts
5. A major “**credit unwind**” is likely is ahead. Debt will become less common.
6. A **major downturn** is not too far away. Some of you may be familiar with the book *Limits to Growth* from the 1970s. It forecast a range of scenarios that might happen when the world hits growth limits. It looks to me as though we may be headed a fairly severe scenario of the type that they modeled. In particular, we may see severe shortages of capital, international financial problems, a decline in globalization, and perhaps even a decline in our ability to make high tech goods that require imports from around the world.

If I have time at the end, I will show a few more slides regarding what happened in the recently.

How Oil Shortages Lead to Economic Decline

First, let's talk about how **oil shortages lead to economic decline**. If there is a shortage of oil, the price of oil may increase, as it did over the period 2003 to 2008. And even now, oil is at a high price, compared to what it was prior to 2008.

The problem when oil prices increase is that quite few prices tend to increase at the same time. For example: food, gasoline or diesel, and home heating oil. The cost of other fuels may increase, too, as they did in 2008, and the cost of metals may increase. The

problem is that even though all these prices are rising, people's salaries are not rising nearly as much.

Food is essential, and gasoline for commuting is essential, so people will cut back on discretionary spending—things like going out to restaurants, or taking vacations, so that they have enough funds to cover their basic needs. They may forego buying a new car, or a new bigger fancier house. This lack of spending tends to cause recession, and people get laid off from work, because people are not buying as many discretionary goods. It also tends to cause a **decline** in housing prices.

The extent to which oil prices need to rise to cause recession will vary depending how much oil a country uses. A country like China that uses little oil, may not have difficulty with recession until the price is quite high. But in the US, where we use a lot of oil, analysis by Dave Murphy of The Oil Drum staff suggests that an oil price of \$80 or \$85 barrel in today's dollars is all that is required to cause recession.¹

Some people believe that efficiency improvements may be sufficient to offset a decline in oil supply. I question whether this will happen. We have a huge number of cars and trucks and much machinery that is already in use. If we are in a recession, we will replace relatively few of these each year, so it will be difficult to make much progress in terms of efficiency.

Why Economic Decline Causes Lots of Defaults

Repaying loans is easy in a growing economy



Repaying loans is much more difficult in a shrinking – or flat - economy



Figure 3. Why repaying loans is easier in a growing economy

Next, let's talk about why **economic decline causes lots of debt defaults**. Let's think about the disks I showed at the beginning. If we are moving from a small disk to a larger disk, it is a lot easier to find the funds to prepay the loan, plus pay the interest, than when we are moving to a situation where the future holds less and less resources, and these must be stretched farther. After we have repaid the loan plus interest, we find we have less left over than we expected, when we took out the loan, and this means we will likely have to cut back on something else.

Clearly if an economy is shrinking, this same principle holds with government-funded pensions for the elderly. When the size of the pie was growing, it may have looked like there would be plenty of money to fund future promises, but once the pie started shrinking, then it became much harder to have enough funds to go around.

¹ David Murphy, "Further Evidence of the Influence of Energy on the U. S. Economy", *The Oil Drum*, 16 April 2009, <http://netenergy.theoil Drum.com/node/5304>

Thinking About the Economy in General

As long as there is a **growing economy**, a huge number of things seem to go well:

- Property values rise, since there is demand for more homes and businesses
- Layoffs are relatively rare
- Business margins are good
- Government revenue is up
- Easy to implement efficiency improvements – pay for new labor-saving machines, or more energy efficient cars
- Easy to borrow money for capital
- Stock market tends to rise – easy to fund retirement plans
- The funds people have available to spend are **increased above** just what their salaries indicate because of several sources of funds:
 - o Increased debt (for example, a person can buy a car even without savings)
 - o Rising stock market (don't need to save much for retirement, so can spend money elsewhere)
 - o Rising home prices (refinance and pull out the equity)

The catch is that with a **declining economy**, pretty much everything that went well before, now goes badly:

- Property values fall, since there is less demand for homes and businesses
- Layoffs are common
- Business margin are low
- Much more difficult to implement energy improvements – if there is no need to add new equipment, why spend a lot of money on new *efficient* equipment?
- Hard to borrow money for capital
- Stock market tends to decline
- The funds people have available to spend are **decreased below** what their salaries indicated because of
 - o Decreased debt (for example, credit card company won't allow any new credit, but expects you to payoff old balance)
 - o Declining stock market
 - o Declining home prices

Why Lots of Defaults Lead to All Financial Institutions Being in Trouble

The problem is that financial institutions—whether banks or insurance companies, or pension plans—are not set up for lots of defaults. Their equity is quickly eroded. The government can try to cover up the situation for a while—as they have been doing recently—but eventually the truth will come out.

While there are various types of insurance programs set up to handle bankruptcies of financial institutions, they are not set up to handle a situation where problems are widespread. The assumption that is always made in funding these programs that bankruptcy is a very rare independent event.

The Debt Problem is Essentially Unfixable in a Declining Economy

The problem is that loan defaults will always be very high in a declining economy, because many people will be unemployed, and not be able to repay their loans, and because business revenue will tend to decline. There is a way of building these costs into the interest rates through what are called “insurance charges”, but then the interest rates will be very high, so few can afford them.

Long term, I expect many fewer loans will be made. The majority of the loans that are issued will be for very short terms—for example, a loan to cover goods that have been shipped, but for which payment is not expected for 30 days. Even mortgages may be hard to get.

Governments are Becoming Financially Troubled, Too

We are seeing this in a number of European countries now, including Spain. While the underlying reason is oil shortages that flow through the economy in ways we discussed earlier, and these oil shortages cause recession and debt defaults, the way this shows itself in government finances is in banks that need bailing out, and in entitlement programs that are becoming more and more difficult to fund, and in low tax revenue.

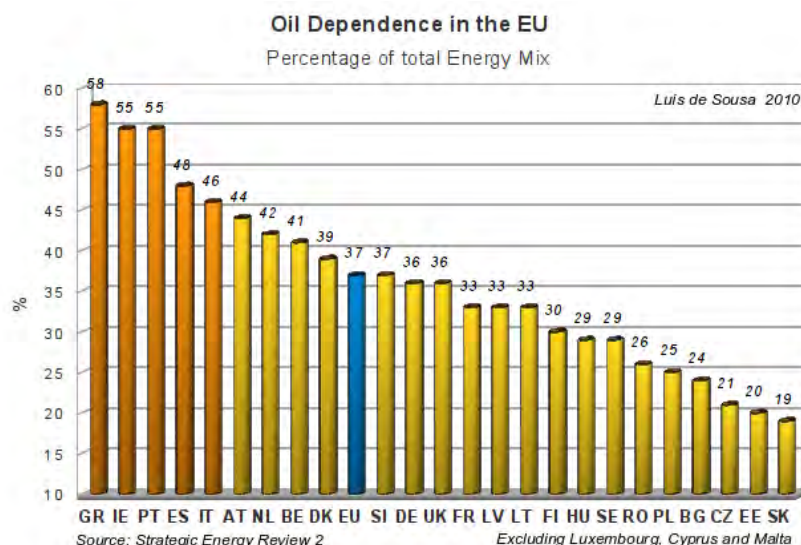


Figure 4. EU countries ranked by their ratio of “oil energy” to “total energy”. Note that the five PIIGS countries use a higher percentage of oil than the other countries of the European Union. By Luis de Sousa. <http://europe.theoil Drum.com/node/7001>

There has been publicity about the PIIGS (Portugal, Ireland, Italy, Spain and Greece) having debt problems. It turns out that the countries that are in most serious financial condition are precisely the ones that get largest percentage of their energy from oil—that is, the once for which the ratio of **oil energy** to **total energy** is highest. The country with the highest ratio is Greece. The second highest is Ireland, and the third highest is Portugal.

There is no easy way out, either, because raising taxes tends to cause more recession, and more debt defaults.

A Major Debt Unwind is Still Ahead

While there has been some reduction in household and business debt, it hasn't gone very far yet, and there has been a big increase in governmental debt to offset the reductions.

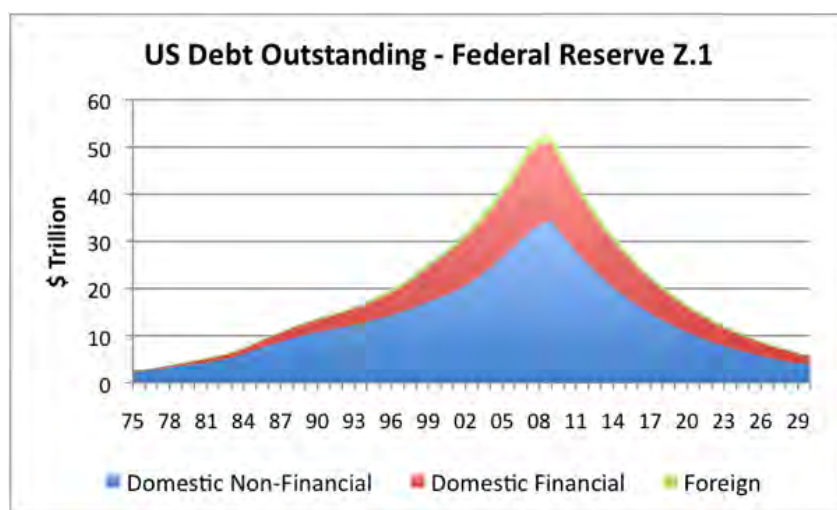


Figure 5. One possible scenario with respect to US debt

Eventually, though, there will have to be a major reduction in debt. I am doubtful that this will be done through a single debt jubilee, however. More likely, some debt will be charged off, a bit at a time, or new delayed payment plans will be provided. Some countries may refuse to sell any more goods (including oil) to counties with obvious problems paying their bills.

One of my concerns is that as this debt unwind takes place, the reduction in debt will tend to have a negative effect on the amount people have available to spend each year, as we discussed earlier. Also, as debt disappears, the usual way of financing new business endeavors will disappear. This will make it much more difficult to fund new energy projects of any kind—oil or natural gas or wind turbines, or new investment in energy efficiency. And nations with debt problems may suddenly find it much more difficult to buy imports, like oil. So the impact of this unwind in debt could be very widespread.

One thing I find interesting is that US consumer debt hit a peak in July 2008, and started declining the same month that oil prices did. Mortgage debt is only published on a quarterly basis, but it hit a peak about the same time. Both continue to decline, with nearly every new report.



Figure 6. Consumer Credit Outstanding from US Federal Reserve Z.1 Report

Substitutes may Decline at the Same Time as Oil – Because of the Debt Unwind

It seems to me that a reduction in debt is likely to reduce demand in general, and this will have an unexpected effect—reducing the demand (and hence supply) of the energy products that might act as substitutes for oil – natural gas, coal, and even nuclear, wind and solar.

Since this isn't very obvious, let's talk about it a bit. Because of less debt availability, fewer people will be able to afford new cars, or new houses, or other big purchases. The result is likely to be a cutback in demand for the fuels used in the manufacturing and transport of these big purchase items--and therefore lower prices for these fuels. This would include oil and natural gas, but it would also include fuels for electricity, including coal and wind and uranium.

Also, with the lower prices, the businesses producing these fossil fuels will have less cash flow (and less profits) to reinvest in their businesses. With the lower market prices, it won't make sense to extract oil, or natural gas, or uranium from the most expensive locations. If locations where low priced fuel can be obtained are mostly tapped out (as they are for oil and natural gas, and even uranium), this means that there will be fewer suitable sources for extraction at prices customers can afford. Even coal may be affected, if there is less electricity used.

With less demand for electricity, utilities can be expected to have less need for new generation of any kind, so nuclear, wind, and solar purchases of the size utilities can be expected to make may be scaled back. There may also be difficulty financing these new sources of electricity, if debt is hard to obtain.

Solar panels are often added to new homes, but if there are few new homes being built, there will be fewer solar panels as well. Homeowners considering adding solar panels may find it difficult to obtain financing for solar panels, too.

I might mention that the extent of the recession and debt unwind may vary around the world. Countries that use little oil (like China and India) may have less of this impact. So they may continue to increase their demand for coal, even as developed countries are cutting back, because of recession. So coal use may not fall worldwide, even though OECD countries are likely to see a cutback in its use.

Major Downturn Likely not Far Away

Because of the many issues that I have outlined, it seems to me that a major downturn is not far away. I think we will be seeing more and more debt defaults, and that even some countries may default.

One of my concerns now is that governments really need to raise taxes, if they are to pay for all of the promised entitlements, and also not default on their debt. The problem is that if they do raise taxes, then citizens and businesses will need to cut back on their spending. This is likely to lead to more recession and more debt defaults.

I am afraid all of this will be very detrimental to **capital availability** for all kinds of investments—oil, or natural gas, or wind, or new factories. One of the major reasons is that debt is likely to be very high priced or not available at all. We are so used to debt financing now, that a cutback in debt is likely to be a huge problem.

It seems to me that if there are a lot of debt defaults, the international financial system may cease to function in the way we are accustomed. Sellers of products, such as oil, may decide that they do not want to trade with buyers who haven't had enough money in the recent past, and may not have enough in the future. This might mean that a country like Greece, or a much bigger country with financial problems, might start encountering problems in buying goods that they were accustomed to buying in the past.

Globalization Needed for High Tech Products

I am concerned that eventually, the globalization that we need for high-tech products may become less available, over a fairly short time-period. We don't think about it, but high tech goods, such as computers and portable telephones, require imports from around

the world—oil, several kinds of metals, and sometimes even rare earth minerals. And to get these necessary materials requires expertise from around the world—for example, a specialist in handling a particular type of problem in drilling oil wells.

Theoretically, if international trade were reduced, we could get along by using recycled materials—perhaps metal from old cars, or from pipes in shopping centers. But these metals would not be as pure. They would work for some goods, but not for others.

World May Change Greatly

It seems to me that the world may change greatly in the next 10 to 20 years, especially if there are major interruptions to international trade. For a while, the difference won't be too great—if something breaks, we will just be able to cannibalize parts from a similar device. But eventually, we will find that the equipment that we use to pull fossil fuels and uranium out of the ground is broken, and cannot be easily replaced, or that wind turbines have stopped working for lack of replacement parts.

It would seem to me that in such a situation, world population would be likely to decline because fuels are not available to produce adequate food and water. There would likely be still some vestiges of globalization for many years, but it would be scaled back greatly.

In many ways, what we experience might be similar to what the Limits to Growth models from the early 1970s suggested might happen, under some of the more adverse scenarios. The problem would be too many people to support with the resources available. We could not keep up our existing level of complexity with our reduced oil supply.

The Past Financial Crisis

If we have a couple of minutes more, I would like to do a flashback, and talk about what happened in the past few years, with respect to the financial crisis. Many people think that oil had nothing to do with what we experienced, but I think they are incorrect.

If we think back to what happened in the US in the early 2000s, the price of oil began rising in quite early in this period. Some of the early response was to try to make debt more available, so as to encourage growth, even if it wasn't "real" growth.

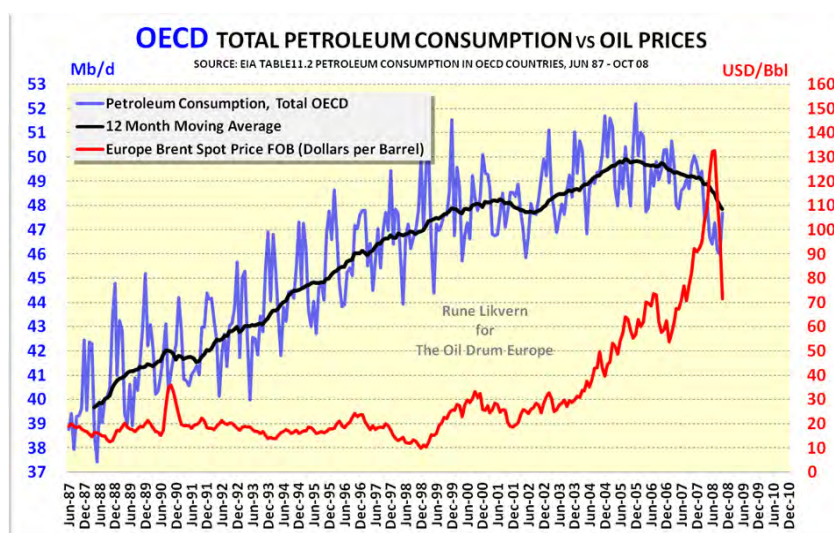


Figure 7. OECD Oil Consumption (blue) compared to Price (red) (Graph by Rune Likvern of www.theoil drum.com)

By 2004, high oil prices were viewed as a problem. The Federal Reserve started raising interest rates, and kept raising them each month, in an attempt to choke back the rise in the price of petroleum products and food. This was in the minutes of their meetings.

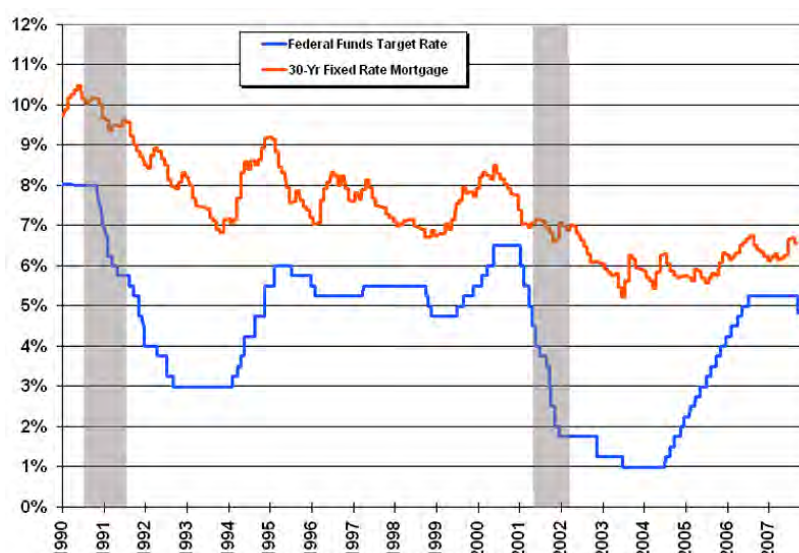


Figure 8. US Federal Funds rate (blue) and average 30 year fixed mortgage rate, based on data of research.stlouisfed.org.

Looking back at Figure 7, by 2006, oil consumption of OECD had started declining. I would argue that part of this partly in response to the higher oil prices in this period, and partly in response to the Federal Reserve's higher target interest rates, which were indirectly the result of higher oil and food prices. So people found themselves with higher costs on home improvement loans, and on business loans, at the same time that oil and food prices were rising.

The Fed—who had raised target interest rates—got a good deal more than it was looking for, because by about the time oil consumption started declining—that is 2006—so did home prices. (Oil prices really didn't come down.)

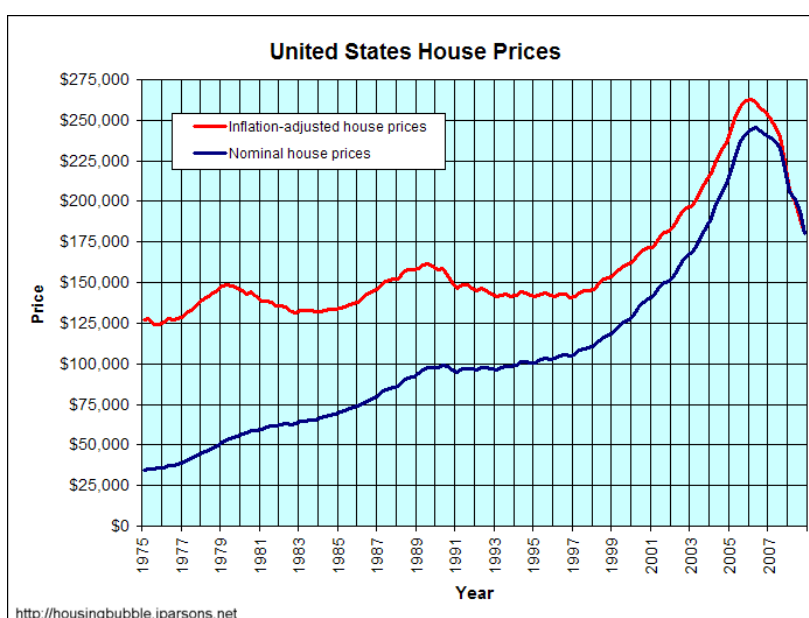


Figure 9. United States Housing Prices from housingbubble.jparsons.net

The stories in US newspapers talked about how home prices in the distant suburbs were particularly affected. Subprime borrowers were particularly affected, but one would expect subprime borrowers to be particularly affected, since any change in the amount of money that they had available to spend would quickly be translated into a cutback somewhere else—and for many, that meant missing mortgage payments.

In 2008 and 2009, we know quite a bit of the story. Oil prices increased to a high of \$147 a barrel in July 2008, but, needless to say, salaries didn't rise accordingly. High oil prices led to a cutback in discretionary spending, and caused people to default on their debts. By July 2008, the tension between the need for higher oil prices and people not being able to afford the high prices was broken, and oil prices began falling. As we saw earlier, credit availability peaked at the same time as oil prices peaked.

It seems to me that oil prices don't just keep rising. Instead, they tend to hit an affordability threshold, and then come back down again. The affordability threshold seems to be related to Energy Return on Energy Invested (EROI). Based on work of Dave Murphy (mentioned earlier), this threshold seems to be in the \$80 to \$85 barrel range for the United States—still too low a level to make most alternatives profitable.

In late 2008, oil prices dropped far below the \$80 - \$85 barrel range, but now it appears that oil prices are again back up to the problem range. So we can expect more defaults, both in the US and in other countries. And, as I said earlier, it looks to me as though we are likely headed for a major downturn in not too many years, similar to what Limits to Growth models from the 1970s suggested.

POSTERS

ANALYSIS OF TECHNOLOGICAL SOLUTIONS

Suomalainen K., Juliano M., Silva C., Connors S., Ferrão P.
WIND SPEED DYNAMICS IN COASTAL AREAS VS. MOUNTAIN RANGES –
IMPLICATIONS OF DIURNAL VARIABILITY IN URBAN WIND POWER

Bravi M., Parisi M. L., Tiezzi E. and Basosi R.
LIFE CYCLE ASSESSMENT OF ADVANCED TECHNOLOGIES FOR
PHOTOVOLTAIC PANELS PRODUCTION

Carrasquer B., Uche J. and Martínez A.
CALCULATING THE EFFICIENCY OF CURRENT HYDROPOWER
TECHNOLOGY IN THE SEGRE-NOGUERA PALLARESÀ BASIN FROM THE
EXERGY APPROACH

Círez F., Bayod A. A., Uche J., Martínez A.
WATER SUPPLY IN THE CIRCE ZERO EMISSION BUILDING: RELIABLE
ED+PV SYSTEM SIZING

Cetin E., Yilanci A., Ozturk H. K., Hekim M., Kasikci I., Colak M., Icli S.
SIMULATION AND APPLICATION OF A DC ENERGY DISTRIBUTION SYSTEM
FOR HYBRID RENEWABLE ENERGY SYSTEMS

Uçkan G., Öztürk H. K., İçli S.
MATHEMATICAL MODELING AND SIMULATION OF HYBRID PARABOLIC
SYSTEM IN KIZILDERE DENİZLİ TURKEY

Bertrand A., Koster D.
DETAILED ENERGY CONSUMPTION ASSESSMENT OF DIFFERENT
SUPERMARKET REFRIGERATION CONFIGURATIONS IN LUXEMBOURG

Kawakami M. and Yamanaka K.
SPECIAL PAINT APPLICATIONS FOR ENERGY SAVING AND CO₂ EMISSION
REDUCTION IN WINTER

Ishimatsu K., Leach M., Ito K., Mitani Y.
GREEN ROOFS FOR URBAN AREAS: EFFECT OF IRRIGATED-SOIL
COVERED ROOFS FOR COOLING

Kvesitadze G., Sadunishvili T., Dudaauri T., Metreveli B., Jobava M.
TWO-STAGE ANAEROBIC PROCESS FOR BIO-HYDROGEN AND BIO-
METHANE COMBINED PRODUCTION FROM BIODEGRADABLE SOLID
WASTES

Benini L., Torri C., Bandini V., Marazza D., Marotta L., Contin A.
AGRICULTURAL RESIDUES FOR ENERGY PRODUCTION AND CARBON
STORAGE INTO SOILS: A WIN – WIN OPTION?

WIND SPEED DYNAMICS IN COASTAL AREAS VS. MOUNTAIN RANGES – IMPLICATIONS OF DIURNAL VARIABILITY IN URBAN WIND POWER

Kiti Suomalainen^{*1,2}, Manuela Juliano³, Carlos Silva^{1,2}, Stephen Connors^{1,4}, Paulo Ferrão²

¹ MIT Portugal Program

² Technical University of Lisbon, Portugal

³ LAMTec, University of the Azores, Portugal

⁴ Massachusetts Institute of Technology, Cambridge, USA

ABSTRACT

This paper presents the application of a new approach for taking into consideration the variability of an intermittent energy resource, the wind in this case, at different temporal scales (hourly, daily, monthly, annual) in scenario construction for energy systems modelling. It is argued that commonly used one-step, two-step Markov models, and AR(MA) models do not contain enough low frequency information meaning that eventual stronger winds during a certain time of day, e.g. afternoon winds, are neglected. A new methodology that evaluates the occurrence frequency of different wind day types, such as afternoon winds or morning winds, is applied on one hand to wind data from locations with high average wind speeds and little diurnal effects and on the other hand to locations with lower average wind speeds but a clear diurnal cycle. The latter locations are close to or in urban areas and the penetration wind power in these locations is compared to that of the on average windier locations. It is concluded that including diurnal has a slight impact on evaluating excess wind power in an energy system in the assessed locations. A more significant impact is expected in locations where the diurnal effect is not as well aligned with the daily demand pattern, such as locations with night winds.

Keywords: renewable resource variability, urban wind power

1. INTRODUCTION

Many wind studies focus on locations with excellent wind conditions for power production, but as urban areas have become a topic of interest for small scale energy production, a detailed characterisation of the available wind resource is essential. Whereas sites with high average annual wind speeds have little or no diurnal effects, areas with lower average wind speeds may show significant diurnal and/or semidiurnal variability. If diurnal effects imply higher wind speeds during daytime or the afternoon when demand is typically high and lower wind speeds at night when demand is typically low, it could allow increasing the penetration rate for wind power without requiring extra storage capacity. It is therefore necessary to develop practices of wind resource evaluation that include the characterisation of diurnal wind patterns and represent them correctly when generating synthetic wind data for energy systems modelling.

The intermittency of the wind resource has been widely studied and many methods for its prediction have been developed (Castellanos and Ramesar, 2006; Billington et al., 1996; Castro Sayas and Allan, 1996). Most of these methods focus on statistical, numerical or physical models to predict hourly wind speeds for up to a few days. What makes the study of diurnal patterns relevant is the match or mismatch with demand patterns. As demand follows a relatively predictable repetitive daily pattern, the 24h period

* Corresponding author; E-mail: kiti.suomalainen@dem.ist.utl.pt; Tel: +351 210407022 (Ext: 5219)

becomes relevant for renewable energy resource characterisation as well. The fact that the wind resource also seems to have diurnal patterns caused by the breeze effect leads to the possibility of better evaluating the resource availability and better dimensioning the system to match overall supply with demand.

The methodology presented in this paper aims at characterizing the wind resource in a manner that allows realistic scenario generation of hourly wind speeds for several years or even decades. The methodology builds on characterising the wind resources by its variability by studying diurnal, including relevant stochastic effects and seasonality, and constructing scenarios that reflect the various possible outcomes based on historical statistical analysis.

The result is not a prediction of the wind speed at a given hour, but a simulation of a possible chain of events. Instead it conveys valuable information for energy systems modelling, that may be used to optimize the system dimensions, in terms of both wind power installed capacity and turbine size.

2. WIND CHARACTERISATION IN ENERGY SYSTEMS MODELLING

Typically long-term energy models assume a constant production from renewables, but as the models' time-steps become smaller and renewable's penetration larger, the renewable energy resource dynamics at different temporal scales is no longer negligible.

Some commonly used method for synthetic wind speed data are independent and identically distributed values (Beyer and Nottebaum, 1995; Gallagher and Elmore, 2009; Chang and Tu, 2007; Elmore and Gallagher, 2009), one- and two-step Markov chain models (Kirchhoff and Syu, 1989; Shamshad et al., 2005; Sahin and Sen, 2001; Nfaoui et al., 2004) and AR(MA) models (Box and Jenkins, 1976; Kennedy, 2003). Kaminsky et al. (1991) tested the first approach with Rayleigh and Weibull distributions. It was concluded that the resulting time series can model the overall wind speed distribution with an acceptable mean and variance, but does not correctly model the power spectral density or autocorrelation function, as the real wind is not a sequence of independent random variables.

One- and two-step Markov chain models use information of previous steps (one or two steps in this case) to determine the probability distribution of the current value. However, the real wind contains more low-frequency information than one- or two-step Markov chain models. Autoregressive moving average (ARMA) models generate a sequence of random numbers which have a prescribed correlation structure, typically used to include seasonal variability to a wind speed time series. However, the autocorrelation function typically includes only a few previous steps, and as such has the same shortcomings as one- and two-step Markov models; the synthetic time series still has less low-frequency information.

Embedded Markov chain method (Kaminsky et al., 1991) is an approach that has two transition probability matrices, one describing rapidly sampled data and the other developed from the long-term average of the data. The two matrices will then constitute a two-step Markov chain, essentially combining a low-frequency transition matrix with a high-frequency transition matrix. The resulting time series agrees in power spectrum comparison as well as the Shinozuka method. However, if the low-frequency matrix is developed to represent seasonal variability, then diurnal variability will still be neglected, and vice versa.

Negra (2008) developed a model for synthetic wind speed time-series generation. Instead of using transition matrices for evaluating the next state, their model uses a birth-and-death Markov chain with state transition rates for evaluating the residence time of each state. First a wind speed probability table is defined, with state frequency and duration information. Second, a set of wind speed time series is defined from that table. The model assumes: a discrete number of wind speed states, statistical stationarity i.e. the stochastic behaviour is independent of which point of time is being considered,

exponential distribution of residence times in a given state of the birth-and-death process, direct proportionality of the probability of transition from one state to another to the long-term average probability of the new state, and that only transitions to immediately adjacent states are possible. Seasonal variability is considered by defining 12 probability tables, one for each month. Diurnal characteristics are not considered in the model, but it is discussed that these 12 tables could be further split into day and night data.

3. METHODOLOGY

In the new approach a set of daily wind speed profiles are defined using a different probability of occurrence for each profile, depending on both the season, or month, and on the profile of the previous day(s). Defining a probability matrix for each event, and the transition matrices for going from one event to another, one can generate scenarios with realistic variability at all relevant time scales. "Typical" days will dominate while uncommon events will not be neglected either. The developed methodology consists of the following four steps:

1. Identifying diurnal patterns from wind data set.
2. Determining probability transition matrices.
3. Sampling daily profiles.
4. Sampling hourly variability.

The monthly average wind speeds are calculated in order to adjust the generated synthetic data to the monthly average in step three. Five different day types are defined: days with little variability and days with the highest energy availability on one of the four six-hour periods starting from midnight, as listed below:

1. Days with no significant variability along the day.
2. Days in which most energy is available between 00:00 and 06:00.
3. Days in which most energy is available between 06:00 and 12:00.
4. Days in which most energy is available between 12:00 and 18:00.
5. Days in which most energy is available between 18:00 and 24:00.

Wind energy availability is evaluated as the sum of the cube of the wind speed per hour in each period, and is directly related to the energy that could be produced if a wind energy conversion device was installed there.

The mean and standard deviations for each one of each day type are also calculated for later use in step four. After this step, one has a sequence of average daily wind speeds and the corresponding day types.

Using the information from the first step, two transition matrices are determined. As weather systems typically take two to eight days to pass an area (Burton, 2001), it is reasonable to consider that the average wind speed of a day is not independent of the average wind speed of the previous day. Therefore the first probability matrix gives the probability distribution of the average wind speed for day n depending on the average wind speed of day $n-1$.

The second transition matrix gives the probability distribution for the day type depending on the average wind speed of the day. The results show that the occurrence frequency of each day type either increases or decreases with the average wind speed of the day.

The combination of an average daily wind speed and a day type gives the wind profile for that day. In this step first a set of average daily wind speeds is sampled, for example for a year, from the first transition matrix. The average wind speed of day 1 is taken as the monthly average of January. These wind speeds are then scaled with the monthly average wind speeds to include seasonal variability. The second transition matrix is then used to sample a day type for each day of the year.

The hourly variability is generated in three steps. First a new random value between zero and one is generated, multiplied by the standard deviation of the distribution of values for that hour and added to the mean value of that hour. Autocorrelation is included by taking a weighted mean of the new random value and the wind speed values of two previous hours. The resulting daily profile is scaled to conform with the average wind speed of the day.

4. APPLICATION

The methodology is applied to wind data from six different location on three different islands of the Azores archipelago; a mountain region with data from an existing wind park and an urban area with data from meteorological station from each island. A summary of the data is given in table 1. The study includes two main aspects of comparison. The first is to compare results of using synthetic wind data with and without diurnal effects and the second is to compare the performance of different size turbines in the different wind regimes. Seven different turbines are compared using the software HOMER Energy (HOMER, 2009).

Table 1. Wind speed data information.

	Location type	Annual average wind speed [m/s]	No. years of data	Ground level altitude [m]	Weibull scale parameter	Weibull shape parameter
Santa Maria	Urban	5.8	5	100	6.45	1.94
Santa Maria	Mountain	7.4	3	150	8.08	1.6
Graciosa	Urban	5.2	4	25	5.81	1.91
Graciosa	Mountain	8.9	4	360	9.89	1.81
Faial	Urban	5.1	4	60	5.68	1.69
Faial	Mountain	7.4	3	210	8.31	1.69

Figure 1 gives the probability distribution of different day types, as identified in step one, for the six different locations. The urban locations have a higher diurnal effect, as afternoon winds are most common for all urban locations. In the locations of the wind parks, some day types are more common than others, but there is no clear diurnal effect of one dominating day type.

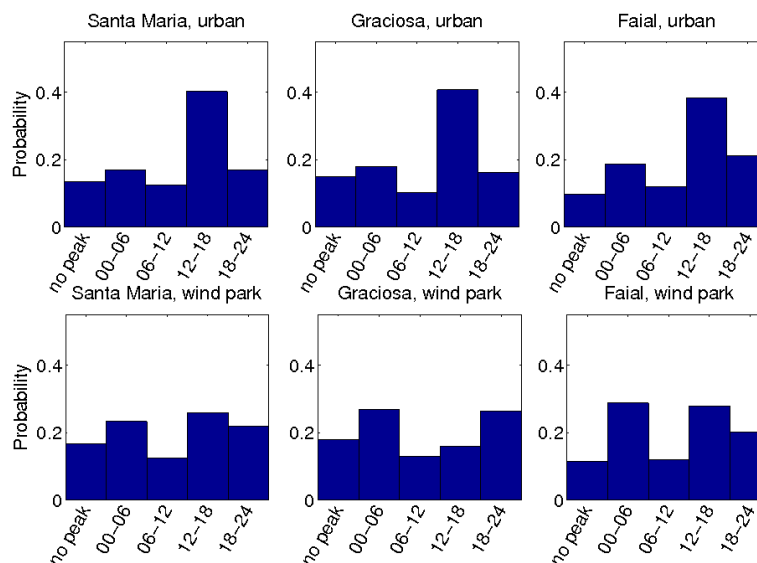


Figure 1. The occurrence frequency of the five defined day types in the different locations.

5. RESULTS

To compare turbine performance the capacity factors, which compare the turbine's actual production over a given time period with the amount of power the plant would have produced if it had run at full capacity for the same amount of time, are calculated (Fig. 2). The mountain regions clearly produce more energy than the urban areas. The rated power per turbine is, from left to right, 2.5, 25, 250, 250, 330, 1500 and 1650 kW, respectively.

To understand the implications of diurnal wind effects on the power system, the three islands' power systems were simulated in HOMER software. Although the demand varies from island to island, a wind park of the same size, ten 330 kW turbines, was simulated for each case. The main results are summarized in table 2. The last column gives the ratio of excess wind power without diurnal effects to excess wind power with diurnal effects in the wind data.

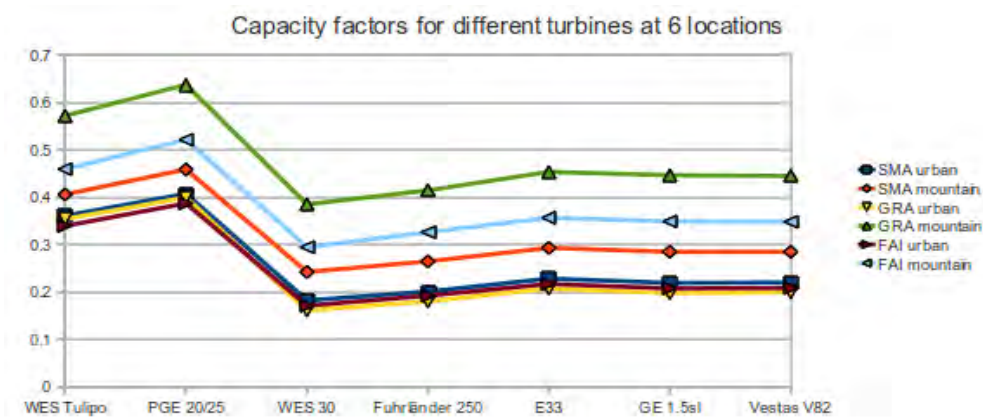


Figure 2. Capacity factors calculated for seven different turbines at three mountain regions and three urban regions.

Table 2. Comparison of wind power in an energy system with and without diurnal effects.

	Location	Diurnal effects	Load (kWh/yr)	Total wind (kWh/yr)	Excess wind (kWh/yr)	Exc ess wind ratio
Santa Maria	Urban	Yes	20 053 714	6 616 303	745 337	
Santa Maria	Urban	No	20 053 714	6 718 675	797 649	1.07
Santa Maria	Mountain	Yes	20 053 714	8 484 061	1 417 499	
Santa Maria	Mountain	No	20 053 714	8 342 079	1 361 432	0.96
Graciosa	Urban	Yes	13 036 165	6 012 325	1 386 880	
Graciosa	Urban	No	13 036 165	6 009 654	1 395 754	1.01
Graciosa	Mountain	Yes	13 036 165	13 114 549	5 304 412	
Graciosa	Mountain	No	13 036 165	12 896 153	5 060 196	0.95
Faial	Urban	Yes	53 128 220	6 286 992	3 216	
Faial	Urban	No	53 128 220	6 532 625	10 017	3.11
Faial	Mountain	Yes	53 128 220	10 318 380	15 346	
Faial	Mountain	No	53 128 220	10 012 985	21 956	1.43

6. DISCUSSION

The comparison capacity factors of wind turbines gave coherent results in ordering the locations in order of decreasing average wind speed. However, while medium size and large turbines gave similar capacity factors on all sites, the small turbines seem to give significantly better results. It must be noted though that the rated capacity range extends from 2.5 kW to 1650 kW, meaning that 660 of the smallest turbines should be installed to achieve the same rated capacity of one of the largest turbines. Also, the power curves, which are used to calculate the energy output at a given wind speed, of small-scale turbines are generally not as reliable as for larger turbines and this may explain the unusually high capacity factors.

Comparing what implications including diurnal effects of the wind may have on the power system showed that the difference in excess wind power was noticeable but not highly significant. The ratio of excess wind in the two cases is more significant for Faial, which has the highest load. This case also has the highest ratio of wind power that is accepted to the grid, since it has the smallest ratio of wind power related to load. This explains the higher value in the last column. It can also be seen that the mountain regions with higher average wind speeds, the cases with no diurnal effects generally lead to lower ratios of excess wind power and in the urban location, the cases including diurnal effects give lower excess wind. This can be expected since the urban locations had more pronounced diurnal effects and since afternoon winds are most common, as demand is also high at that time, less energy will be wasted. For future work, a similar comparison could be made for locations with for example higher wind speeds at night time.

ACKNOWLEDGEMENTS

This paper is part of a doctoral research topic and is funded by the Portuguese National Foundation for Science and Technology. EDA (Electricity of the Azores) and IM-DRA (The Institute of Meteorology - Regional Department of the Azores) are gratefully acknowledged for providing all wind data used in this study, for the wind parks and meteorological stations, respectively.

REFERENCES

- Beyer, H. G., Nottebaum, K., 1995. "Synthesis of long-term hourly wind speed time series on the basis of the European wind atlas data." *Solar Energy* 54 (5), 351–355.
- Billington, R., Chen, H., Ghajar, R., 1996. "A sequential simulation technique for adequacy evaluation of generating systems including wind energy". *IEEE Transactions on Energy Conversion* 11 (4), 728–734.
- Box, G. E. P., Jenkins, G. M., 1976. *Time Series Analysis: Forecasting and Control*. Holden-Day.
- Burton, T., S. D. J. N. B. E., 2001. *Wind Energy Handbook*, 2nd Edition, John Wiley & Sons, Ltd, Chichester, England.
- Castellanos, F., Ramesar, V. I., 2006. "Characterization and estimation of wind energy resources using autoregressive modelling and probability density functions." *Wind Engineering* 30 (1), 1–14.
- Castro Sayas, F., Allan, R. N., 1996. "Generation availability assessment of wind farms". *IEEE Proceedings - Generation, Transmission and Distribution* 143 (5), 507–518.
- Chang, T.-J., Tu, Y.-L., 2007. "Evaluation of monthly capacity factor of wecs using chronological and probabilistic wind speed data: A case study of Taiwan". *Renewable Energy* 32, 1999–2010.
- Elmore, A. C., Gallagher, R., 2009. *Using regional climate center data to predict small wind turbine performance. Practice Periodical of Hazardous, Toxic, and Radioactive Waste management* (January), 14–19.
- Gallagher, R., Elmore, A. C., 2009. "Monte Carlo simulations of wind speed data". *Wind Engineering* 33 (6), 661–673.

- HOMER, 2009. *The Micropower Optimization Model, Ver. 2.68 Beta*. HOMER Energy, LLC, 885 Arapahoe Ave., Boulder, CO 80302, USA.
- Kaminsky, F. C., Kirchhoff, R. H., Syu, R. H., Manwell, J. F., 1991. "A comparison of alternative approaches for the synthetic generation of a wind speed time series". *Journal of Solar Energy Engineering* 113, 280–289.
- Kennedy, S., R. P., 2003. "A probabilistic model for simulating long-term wind-power output". *Wind Engineering* 27 (3), 167–181.
- Kirchhoff, R. H., K. F. C., Syu, S. Y., 1989. "Synthetic of wind speed using a markov process". *Proceedings of the Eight ASME Wind Energy Symposium, Jan., 17–22*.
- Negra, N. B., H. m. O., 2008. "Model of a synthetic wind speed time series generator". *Wind Energy* 11, 193–209.
- Nfaoui, H., Essiarab, H., Sayigh, A. A. M., 2004. "A stochastic markov chain model for simulating wind speed time series at tangiers, morocco". *Renewable Energy* 29, 1407–1418.
- Sahin, A. D., Sen, Z., 2001. "First-order markov chain approach to wind speed modeling". *Journal of Wind Engineering and Industrial Aerodynamics* 89, 263–269.
- Shamshad, A., Bawadi, M. A., Wan Hussin, W. M. A., Majid, T. A., Sanusi, S. A. M., 2005. "First and second order markov chain models for synthetic generation of wind speed time serie". *Energy* 30, 693–708.
- Shinozuka, M., Jan, C.-M., 1972. "Digital simulation of random processes and its applications". *Journal of Sound and Vibration* 25, 111–128.

LIFE CYCLE ASSESSMENT OF ADVANCED TECHNOLOGIES FOR PHOTOVOLTAIC PANELS PRODUCTION

Mirko Bravi^{*1}, Maria Laura Parisi², Enzo Tiezzi^{1,2} and Riccardo Basosi^{1,2,3}

¹ *Polo Universitario Colle di Val d'Elsa, Siena, Italy*

² *University of Siena, Italy*

³ *Centre for the Study of Complex Systems, Siena, Italy*

ABSTRACT

The study, developed through a detailed analysis of available data in the international literature, aims to understand better the nature and the extent of risks related to all stages of photovoltaic panels life cycle, produced by the most advanced technologies. For example, the CdTe (Cadmium Telluride) thin film photovoltaic technology is very promising from an economic and energetic point of view, but it shows challenges and risks related to the presence of a potentially very dangerous heavy metal, whose utilization has been actually banned in many products. Currently, CdTe photovoltaic panels are not included in European regulations limiting elements considered dangerous and that regulating their disposal.

In terms of environmental impact studies, Life Cycle Analysis showed that the CdTe modules have similar or less impact than other photovoltaic technologies and have a lower energy consumption relative to the production stage. Indeed, these studies are developed on the only energetic return and EPBT (Energy Pay-Back Time) basis, and they do not take into account the effects related to heavy metals pollution. In this context, the CIGS (Copper Indium Gallium di-Selenide) and amorphous/micromorph MCPH thin-film silicon technologies showed to have an environmental impact comparable to that of CdTe and in some cases even less.

The lack of ascertained data on the extent of risks associated with production, use and disposal stages of these panels and the fast technological progress of solar technologies make difficult but necessary to outline a reliable framework and to assess a balance between risks and benefits in the use photovoltaic modules on a large-scale. It is also urgent to implement an efficient action for the recovery and recycling based on the precautionary principle.

Keywords: LCA, Photovoltaic, Thin Film, CdTe, Micromorph

* Presenting author: Maria Laura Parisi (parisi11@unisi.it)

CALCULATING THE EFFICIENCY OF CURRENT HYDROPOWER TECHNOLOGY IN THE SEGRE-NOGUERA PALLARESÀ BASIN FROM THE EXERGY APPROACH

Beatriz Carrasquer , Javier Uche and Amaya Martínez*

CIRCE, University of Zaragoza, Spain

ABSTRACT

Most European countries are being more and more conscious of the increment in their water resources demands. Consequently, an environmental-concern has been emerging, mainly throughout last ten years. The Water Framework Directive (WFD) adopted in 2000 constitutes a key point to recover the good status of water bodies. The degradation provoked by water use implies significant variations in its quantity and quality. The restoration costs of those water bodies can be estimated by applying the Second Law of Thermodynamics.

In this contribution, the Segre basin (a tributary from the Ebro River, Spain) was modelled by a specific simulation software providing quantity and quality modules to simulate flow and quality patterns. Restoration costs based on physical degradation of water were calculated and furtherly disaggregated between diverse water users of the basin, in order to allocate the corresponding withdrawal taxes among the different user sectors. However, a different analysis must be carried out when the hydroelectric user is considered. When a hydroelectric facility is placed along the river basin, an additional height gap, which constitutes an economical opportunity for the user, exists. And the main task to be solved here is if the taxes proposed to be paid for this user are adequate. Additionally, the hydroelectric use operation rate was analyzed by two parameters along different hydrologic years. First of them, the Hydropower use of River Index (HyPURI), considers the installed capacity. The other, named as the Hydropower generation in the River Index (HyGRI), is calculated taking into account the hydropower generation. Results showed that the operation rate taking into account the hydropower generation remains constant and close to 0.073 despite of the hydrologic behaviour. On the other hand, the operation rate which considered the installed capacity varied from 0.13 to 0.27, being a useful analysis tool to optimize the available hydropower potential in the river. Finally, a preliminary economical analysis shown that the benefit obtained by kWh are five times higher than the taxes proposed to be paid for the hydroelectric user by the authorities. However, some environmental groups proposed taxes which are more than 20 times the obtained benefits by m³ turbinad.

Keywords: Exergy analysis, Ebro river, hydropower

1. INTRODUCTION

The Water Framework Directive (WFD) came into force in 2000 with the main purpose of establishing a framework for the protection of inland surface waters, transitional waters, coastal waters and ground-waters. It defines the methods, procedures and indicator parameters for characterising the condition of water bodies, and the strategies and instruments needed to protect this condition and to regenerate it (if necessary) [European Commission, 2009]. The condition of all water bodies and its ecological status has firstly to be evaluated, by using quantitative and qualitative parameters and identifying the associated pressures, impacts and risks conditioning that status. Then, not only economic instruments for a good water management, based

* Corresponding author; E-mail: becarras@unizar.es

on the principle of recovery of costs, but also public participation in decisions related to water management, must be taken into account.

According to the article 9 of the WFD, environmental costs would be allocated among different users [European Commission, 2009].

Diverse profiles could be analyzed depending on the WFD effectiveness, as it follows:

- Future State (FS) of the river is understood as the probable state of the river by 2015, starting from present state (PS) of the water stream but introducing the projected pressures (as an example, the percent of increase in water demands).
- Objective State (OS) is that state proposed by authorities as the good status of the river in order to fulfill with the WFD requirements.
- Natural State (NS). It is defined as the state that would be reached in a river without the human pressures given by uses.

2. METHODOLOGY

As previously said, water uses degrade water bodies and, in the same way, its chemical and physical characteristics must be changed up to the required conditions to be used. These conditions depend on the objective of its later uses.

The energy available in a natural resource to produce work is theoretical and equal to the material's exergy value (B). That thermodynamic parameter, considered here as the startup accounting tool, can be calculated as the product of flow (Q, given in m³/s), and specific exergy (b, given in kJ/kg of water) defined by its mass flow and six parameter measurements that characterize its physical conditions: mass flow, as well as temperature, pressure, height, velocity, concentration and composition [Martínez, 2009; Valero et al, 2009; Martínez et al, 2010]. Therefore, the river profile could be fully created as a set of Q and b pairs along the river course. It would provide info about the exergy behaviour of different water components.

According to the European legislation, the environmental cost (EC) of water regards the alteration of the physical and biological aspects of water bodies due to human activities and represents the average cost damage that water uses impose on the environment and their ecosystems. This description of EC was connected to the exergy concept within the PH methodology, defined as the specific application of Thermodynamics to physically characterize the degradation and further restoration of water bodies [Martínez, 2009; Valero et Al, 2009]. The EC was defined within the PH methodology, as the difference between the exergy of a water body in the real state, and the exergy in the objective state of that river by 2015 defined as its good ecological state (Eq. 1):

$$EC = \Delta B_{OS-FS} = B_{OS} - B_{FS} = b_{FS} \Delta Q + Q_{OS} \Delta b = \Delta B_m + \Delta B_q \quad (1)$$

Where ΔQ and Δb are the flow and specific exergy gaps between two exergy states, and m and q stands for quantity and quality exergy components, respectively.

The above developed methodology was used to carry out the calculation of restoration costs, in order to allocate them among the different river users. Different water scenarios, one for each kind of user, were considered, and compared with a state without uses.

These exergy gaps, obtained by applying Eq. 1, were used to calculate the contribution of each user to the total exergy gap within the river. Different exergy contributions were calculated, as follows: the Inorganic Matter (IM), which stands for inorganic salts and water; and the Nitrogen-Phosphorous (NP) component, which accounts for the nitrogen and phosphor in the water flow, in form of nitrates, nitrites,

ammonia and phosphates. The exergy of Organic Matter (OM), thermal and potential components were also calculated (per month of each of the different simulated year, in different river stretches).

2.1. Considerations about the hydroelectric user

When a hydroelectric facility is placed along the river basin, an additional height gap appears. However, water composition remains constant. That is why some components as inorganic, organic, or nitrogen and phosphorous content are affected by irrigation and urban users, whereas the ΔB provoked by hydroelectric facilities, which also contributes to the EC, falls in the potential component defined in Eq. 2. It depends on the flow (Q), the height gap (ΔH) and the gravitational constant (g), for each river stretch (i).

$$\Delta B_p = \sum_i (B_{p,HU} - B_{p,WHU})_i = \sum_i (Q \cdot \Delta H \cdot g)_i = \sum_i (Q_{HU} \Delta b + b_{WHU} \Delta Q)_i \quad (2)$$

The HU stands for the state with hydroelectric users, and WHU represent the river state without them.

Since this exergy gap constitutes an economical opportunity for the hydroelectric user, one of the aims of this work is to analyse if the proposed taxes to be paid by this user are adequate compared with its obtained benefits.

The operation percentage of the theoretical available potential in the basin for that technology which is currently in operation is analyzed here to quantify the hydroelectric use in the river. It is calculated by two dimensionless indexes: the Hydropower use of River Index (HyPURI), and the Hydropower generation in the River Index (HyGRI). The former was defined as the hydroelectric installed power capacity (RHyP_C) along the river course divided by the potential component contained in the whole basin (Eq. 3). The later stands for the ratio between the real hydropower generation (RHyP_G) along the river course and the maximum hydroelectric theoretical generation which could be obtained by pumping all the available water in the basin (Eq. 4).

$$HyPURI = \sum_i (RHyP_C / (Q \cdot \Delta z \cdot g))_i \quad (3)$$

$$HyGRI = \sum_i (RHyP_G / (Q \cdot \Delta z \cdot g \cdot h_y))_i \quad (4)$$

Where i represent a river stretch, Δz is the natural height gap between two consecutive river stretches, and h_y stands for the number of maximum available hours during the year to run the hydropower facilities. The higher value of these indexes, the bigger operation rate by hydroelectric use in the basin.

With the aim of illustrating the applicability of the above mentioned methodology, the case study of the Segre river (a tributary of the Ebro, the most plentiful river in Spain) was developed by using a specific hydraulic simulation software. A brief overview of the case study is included in section three. Final figures and main conclusions are summarized in sections four and five, respectively.

3. THE SEGRE RIVER CASE STUDY

With 261 km length, the Segre is the main tributary of the Ebro (Spain) entering at its North side. Its basin comprises territories across three states: Andorra, France and Spain. Its hydrologic behaviour is random as many other Mediterranean rivers. It varies greatly from minimum values of 0.30 m³/s (sever droughts) to maximum punctual flows of 5,200 m³/s along its medium course. Dams and channels are the main agents in flow regulation. Special mention must be devoted to Oliana Dam and Serós channel. Spring runoffs and autumn rains contribute greatly to water flows growth. The average

contribution of this river is about 3,000 hm³ per year, and its source elevation, 2400 m. It flows into Ribarroja dam, at 75 m above the sea level [Hispagua, 1999].

3.2. River simulation and degradation by water users

The Segre was simulated by a specific software called Aquatool-DMA, developed by the Polytechnic University of Valencia. It contains two independent modules to simulate flow (SIMGES) and quality (GESCAL) patterns, respectively, of a river basin [Aquatool-DMA, 2009]. The main stretches of the river are summarized in Table 1 according to the numeration designed when the basin was simulated. It is represented in figure 1 at the end of this section.

Table 1. Segre river main stretches

STRETCH NUMBER	RIVER	STRETCH NUMBER	RIVER	STRETCH NUMBER	RIVER	STRETCH NUMBER	RIVER	STRETCH NUMBER	RIVER	STRETCH NUMBER	RIVER
1	Segre	10	Salada	19	Boix	29	Farfaña	39	Segre	49	Noguera Pallaresa
2	Segre	11	Segre	20	Segre	30	Segre	40	Sed	50	Noguera Pallaresa
3	Segre	12	Seg.- Garrig. Channel	21	Urgell	31	Segre	41	Segre	51	Noguera Pallaresa
4	Valira	13	Seg.- Garrig. Channel	22	Urgell	32	Chan.	42	Segre	53	Noguera Pallaresa
5	Vansa	14	Segre	23	Segre	33	Cervera	43	Noguera Pallaresa	54	Noguera Pallaresa
6	Segre	15	LLobr.	24	Segre	35	Segre	44	Noguera Cardós	55	Noguera Pallaresa
7	Segre	16	Urgell	26	Síó	36	Sed	45	Noguera Pallaresa	56	Urgell Channel
8	Segre	17	Urgell	27	Cervera	37	Seg.- Garrig. Channel	46	Flamisell	57	Segre
9	Segre	18	Segre	28	Corp	38	Seg.- Garrig. Channel	48	Noguera Pallaresa		

The specific quality module makes possible to take into account, for several hydrologic years, aquifers, dams, diffuse returns, dangerous substances, or hydroelectric plants. Finally, its capacity of linking and editing GIS data fields, assure a flexible and reliable simulation tool. Input monthly flows data for each year within the 2002-2007 period were introduced in the Aquatool-GESCAL interface. In particular, the modelled quality inputs parameters were sulphates, alkalinity, calcium, sodium, magnesium, chlorine, organic matter, nitrates, ammonium (in kg component/m³), and conductivity (s/cm). The calibration of these input flow required to carry out with mass balances with the different water flows, by using the SIMGES program module, which deals with quantity figures. Quality data given by quality control stations along the river course were used to simulate quality water inflows in river stretches. The data were taken from [CHE, 2009]. Water deterioration provoked by the different water uses (urban, agriculture and hydroelectric) was studied. Return ratios for different uses (80 and 20 percent for urban and agriculture, respectively) [Hernández, 2001], as well as from the elimination ratios of the existing Wastewater Treatment Plants and the pollution ones for different users [Hernández, 2001; INE, 2007; IAA, 2005] were considered. Additionally, monthly evolution of temperature, dam related data as evapo-transpiration and level-capacity curves found in [CHE, 2009] were also introduce in the

analysis. Quantity and quality flow data were obtained, per month of each simulated year and stretch. Then, exergy profiles could be calculated. By using (Eq. 1), the quantity and quality components could be individually studied.

The hydropower generation was analyzed from average monthly data for hydroelectric generation found in [REE, 2010], for different years.

Figure 1. schematizes the Segre river main course including its tributaries. Seven important hydro-power facilities and the Segarra-Garrigues and Urgell channels are also been represented.

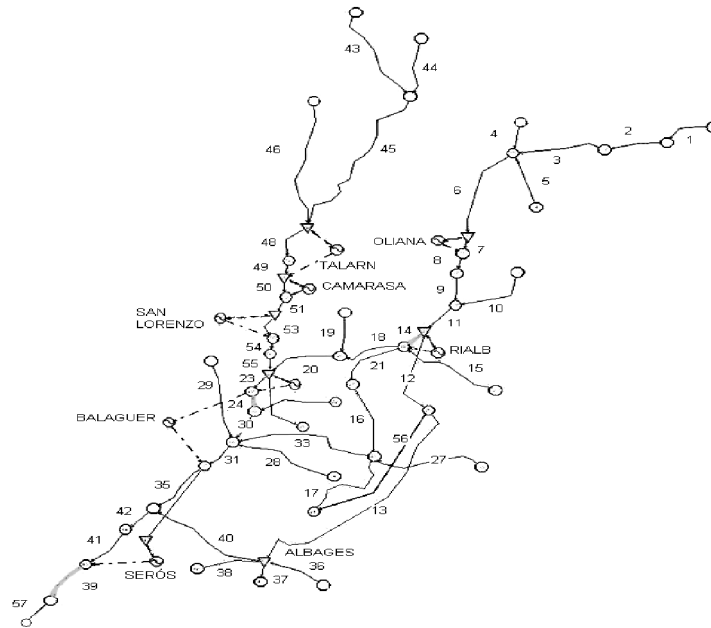


Fig. 1. The Segre basin.

4. RESULTS DISCUSSION

The most important obtained results in the Segre basin are summarized here. From the set of obtained profiles (one per month along 5 simulated years) a representative one with average values along the river for different states is shown in Fig. 2. The PS flow differs from the others due to the fact that the flow regulation by Urgell and Segarra-Garrigues channels which will start to be used by 2015. As a consequence, the flow will be also diminished until the mouth of the river.

As it can be seen in Fig. 2, the points where the flows come close to zero are those representing the stretches located after the hydroelectricity facilities along the main course of the river. This use diminishes the river flow from its Natural State (see Figs. 2 and 3).

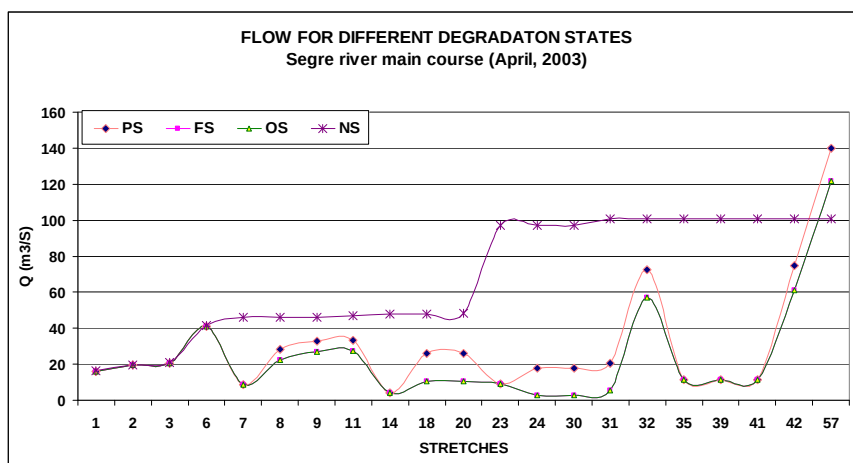


Fig. 2. Flow along the Segre river main course for different degradation states

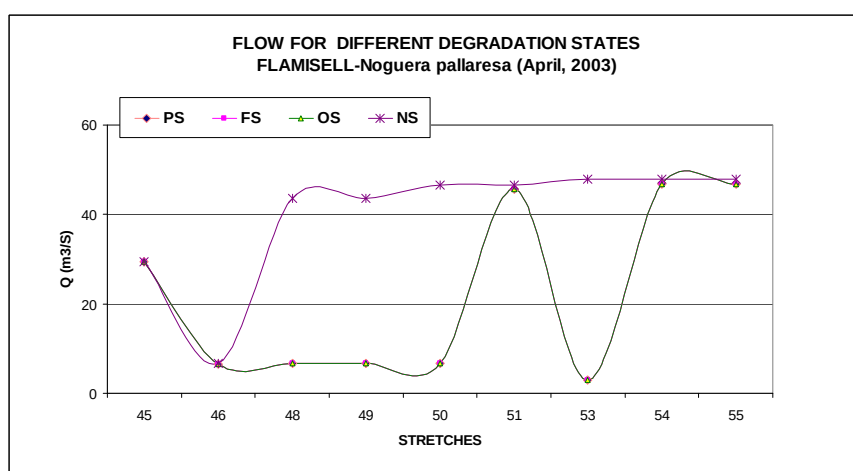


Fig. 3. Flow along the Flamisell - Noguera Ribargorçana for different degradation states

The results obtained for the previously defined hydroelectric use ratios are summarized in Table 3.

Table 3. Hydroelectric indexes for two different hydrologic years

	HIDROLOGIC YEAR 2002-2003 (Wet)	HIDROLOGIC YEAR 2005-2006 (Dry)
HyPURI	0.13	0.27
HyGRI	0.073	0.074

It is worth to highlight that, although these parameters definition is very similar to the Gross Capacity of the river, they are analyzed here for each stretch of the river, and for different hydrologic years. From the results can be conclude that the HyGRY, which takes into account the hydropower generation, remains constant and close to 0.07 despite of the hydrologic behaviour. Both real and theoretical hydropower generation components in the basin change in the same way according to the hydrological behaviour: they rise in wet years and diminish during the dry ones. Nevertheless, the operation rate which considered the installed capacity, HyPURI, varied from 0.13 (in 2002-2003, a wet year) to 0.27 (In 2005-2006, a dry year). In this case, the bigger water availability in the basin (in rainy years), the higher theoretical value of available potential component contained in the basin; on the other hand, the real installed capacity of hydropower facilities remains constant. Consequently, this ratio is useful to optimize the available hydropower potential in the river, considering the expansion of the hydroelectrical real potential in the basin, if necessary.

Results for ΔB_m and ΔB_q components were taken into account to calculate the average water pollution loads (given in ΔB) due to different uses. Then, the contribution of restoration cost by water degradation due to different uses was distributed among them (see Fig. 4).

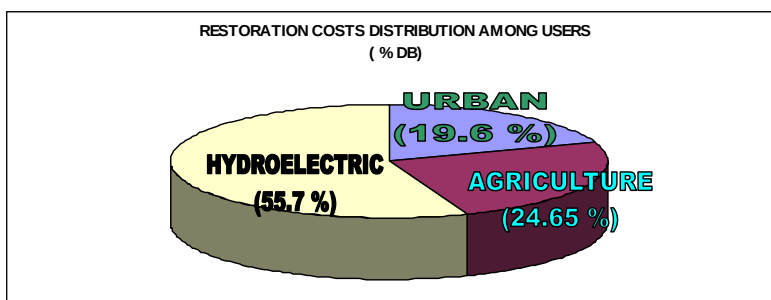


Fig. 4. Distribution of restoration costs among different users (% ΔB total due to uses in the basin)

It can be concluded that the degradation provoked by the hydroelectric user constitutes the 55.7 % of the environmental costs.

A preliminary economical analysis shown that the obtained benefit by kWh is much higher than the taxes proposed by the authorities to be paid for the hydroelectric user. If a price of 70 €/MWh (as a function of the average reference tax for the electricity) is considered, that benefit is five times higher compared with the 14 €/MWh that constitutes the taxes proposed for this use by the Spanish Government [Ministerio de Industria, Turismo y Comercio, 2010]. In Spain, the hydroelectric generation has been growing during last decade, but also the thermal and, as a consequence, the global electricity generation. Then, the contribution of this renewable energy to the global production has diminished. Electricity generation alternatives driven by renewable resources different from the fossil fuels, in depletion, must start to be used. The previously analyzed ratios shown a sub-exploitation of the hydroelectric potential, so the high obtained benefits by this kind of renewable energy could make it rise.

Some environmental groups also proposed taxes for this kind of user, according to [Hispagua, 2010]. Their values are 15 c€/m³, for big hydroelectric facilities, and 7.5 c€/m³, for those facilities which produce less than 500 kW or turbine less than the 30% of the river flow. These quantities are excessive compared with the obtained benefits, since they suppose more than 20 times the obtained benefits of 0.35 c€/m³ turbinado, calculated with data taken from [Endesa, 2007] for these case study.

5. CONCLUSIONS

The main fulfilled goal in this paper consisted on calculating the cost to restore water bodies, or Environmental cost between the state of the river by 2015 and the objective state of the river by 2025, taking into account the WFD road map. In addition, such a cost has to be allocated among water users in fulfilment of the article 9 of the WFD. In this paper, by applying the Physical Hydraulics methodology to the Segre-Noguera Pallaresa basin (Spain), both targets have been covered. Mass flow, apart from physical conditions such as temperature, pressure, height, velocity, concentration and composition were considered to analyze chemically and physically the evolution of each stretch of that basin, for different years, and degradation states. An specific hydraulic software (here Aquatool) provide different water scenarios in order to calculate the exergy gaps among different river states.

The main novelty of this work, which respect to other aims of the authors, is the consideration of the hydroelectric uses. While quantity and quality of water are affected mainly by irrigation and urban users, hydroelectric use only affects to the potential component. Nevertheless, it is important to be considered in the EC accounting, since

it constitutes a key issue in the case study basin because of the high presence of power facilities found in it.

Results show that the degradation coming from the urban and irrigation uses is distributed equitably between them. But the biggest contribution to degradation is provoked by the hydroelectric user and constitutes the 55.7 % of the environmental costs. The operation of hydroelectric facilities, compared with the theoretical available potential in the basin, is lower than the 30 %. Then, that operation rate which considered the installed capacity is a useful tool to optimize the available hydropower potential in the river, considering the expansion of the hydroelectric real potential in the basin, if necessary. Since the obtained values shown a sub-exploitation of the hydroelectric potential in the Segre River, Spain, the high obtained benefits by this kind of renewable energy could made it rise. They are five times higher compared with the taxes proposed by the Spanish Government.

It is worth to highlight that the applied methodology makes possible the individual characterization of the user with each kind of water degradation. Firstly, it allows charging the Environmental costs of the potential component to the hydroelectric user, who obtains a benefit because of the height gap. However, the degradation of quality due to the change into the water composition is accounted in the AB provoked by the agriculture user. A comprehensive evaluation of different hydroelectric technologies would make possible to improve the analysis and to carry with a reliable study of variation of the Environmental Costs, by considering the quality and quantity exergy components in each case. It is nowadays an important goal in progress for coming works.

Nomenclature

b: Specific exergy (kJ/kg water)

B: Exergy (KWh)

EC: Environmental costs

FS: Future State

g: Gravitational constant (m/s^2)

H: Height in a given point

h_y: Maximun Number available hours during the year

HyGRI: Hydroelectric Generation of River Index

HyPURI: Hydroelectric Potential of River Index

Q: Flow (m^3/s)

NS: Natural State

OS: Objective State

PH: Physical Hydraulics

PS: Present State

PM: Plan of Measures

Q: Flow (m^3/s)

RBP: River Basin Plan

RHyPC: Real Hydropower Capacity

RHyPG: Real Hydropower Generation

WFD: Water Framework Directive

WWTP: Waste Water Treatment Plant

Subscripts and superscripts

IM: Inorganic matter

m: quantity

NP: Nitrogen-Phosphorous

OM: Organic Matter

p: potential

q: quality

ACKNOWLEDGMENTS

The authors greatly acknowledge the financial support given to this paper, which is under the framework of the IDERE R+D+I project (ENE2007-067191), financed by the Spanish Ministry of Education and Science.

REFERENCES

- Aquatool-DMA, *quantity and quality water masses simulation software*, October 2009, Software Package. Universidad Politécnica de Valencia. IIAMA. Spain.
- Confederación Hidrográfica del Ebro, 2009, *Datos de la Oficina de Planificación Hidrológica, Ministerio de Medio Ambiente* [available online]. URL [<http://www.chebro.es>].
- Endesa, 2007. *Presas en el mundo. Centrales hidráulicas en España*. Endesa ediciones. Madrid; [in spanish].
- Hernández, A., 2001, *Saneamiento y alcantarillado. Vertidos Residuales*, Colegio de Ingenieros de Caminos, Canales y Puertos, Universidad de Zaragoza, Zaragoza, Spain [in Spanish].
- Hispagua, 1999, *Río y ciudad*, Volumen II, Nº47; Ministerio de medio Ambiente y medio Rural y Marino. URL: <http://hispagua.cedex.es> [in Spanish].
- Hispagua, 2010. "Lleida Ambiental reclama un canon para hidroeléctricas y regantes". *Diario La mañana*; 06-08-2010. Ministerio de Medio Ambiente y Medio rural y Marino; URL: <http://hispagua.cedex.es> [in Spanish].
- Instituto Aragonés del Agua (IAA), 2005, *Medio Ambiente Aragón 2004-2005*, IAA, [online report], URL: <http://portal.aragon.es> [in Spanish].
- Instituto Nacional de Estadística (INE), 2007; *Informe INE, datos 2007*, Technical Report, INE, Madrid, Spain [in Spanish].
- Martínez, A., 2009, *Exergy costs assessment of water bodies: Physical Hydronomics*, Ph.D Dissertation, University of Zaragoza, Aragón, Spain.
- Martínez, A. and Uche, J., 2010, "Exergy of organic matter in a water flow", *Energy* 35 (1), pp. 77-84.
- Martínez, A; Uche, J; Valero, A. and Valero, Al., 2010, "Environmental costs of a river watershed within the European water framework directive: Results from Physical Hydronomics", *Energy*, 35 (2), pp. 1008-1016.
- Ministerio de industria, Turismo y comercio, 2010. *Plan de Energías Renovables en España, 2005-2010*. Technical Report. MITYC. URL [<http://www.mityc.es>]
- REE, 2010. *Balances de producción eléctrica. Technical report. Red Eléctrica Española. 2010*. URL [<http://www.ree.es>].
- The European Commission, 2009, *Report from the Commission to the European Parliament and the Council in accordance with article 18.3 of the Water Framework Directive 2000/60/CE on programmes for monitoring water status*, Technical report, [SEC(2009)415], Commission of the European Communities, Brussels.
- Valero, A., et al, 2009, "Physical Hydronomics: Application of the exergy analysis to the assessment of environmental costs of water bodies. The case of the inland basins of Catalonia", *Energy* 34 (12), pp. 2101-2107.

WATER SUPPLY IN THE CIRCE ZERO EMISSION BUILDING: RELIABLE ED+PV SYSTEM SIZING

Fernando Círez , Angel A. Bayod, Javier Uche, Amaya Martínez*

CIRCE/University of Zaragoza, Centro Politécnico Superior, 50018 Zaragoza

ABSTRACT

The new CIRCE building, sited in the polytechnic campus of the University of Zaragoza, has been conceived as a zero emission building designed to boost the development of energy efficiency and renewable energy systems integrated in buildings. Water and energy supply have been sized following sustainable patterns and trying to achieve as much own provision as possible.

In this paper, the water supply system is explained and analyzed. Although the facility is obviously connected to the city water supply network, the possibility of producing the water demand from water reuse and deep water sources are considered here.

The water treatment required to adapt the quality to the corresponding use is proposed to be achieved by an electrodialysis unit fed by photovoltaics. The different components of a system of this kind are considered: feed water, capacity of the electrodialyzer, photovoltaic field and batteries.

Keywords: Electrodialysis, Photovoltaics, Zero Emissions Building

1. INTRODUCTION

The scientific evidences for climate changes and the associated impacts of greenhouse gas emissions are becoming increasingly noticeable. Both, this phenomenon joined to an increasing lack of potable water, are problems ensued from an important energetic imbalance that can be seen as a great opportunity for the change. But this is not any change and should lead efforts to promote the incorporation of renewable energy, as well as energy efficiency, to benefit society and the environment.

An example of these necessary incorporations of renewable energy is the recently concept of Zero Emissions Buildings as pointed out by numerous authors as Wang et al (2009) or Hernández et al (2010). That designations apply to a with a net energy consumption of zero over a typical year. It implies that the energy demand for heat and electrical power is reduced and sized following sustainable patterns, in order to meet these requirements from renewable energy supply. These kinds of buildings are not designed as off-grid systems but the grid is used to supply electrical power when there is no renewable power available, and the building will export power back to the grid when it has excess power generation. As mentioned the energy balance at the end of the year, produced by these inputs and outputs between the building and the electrical grid must be positive or zero.

To sum up, the object of a Zero Emissions Building is to join together the minimization of resources loads by though constructive elements (materials and orientation) and the integration of renewable technologies in order to satisfy them.

The energy efficiency measures together with the possibility of treating phreatic and/or any other natural water source near to the place of consumption, an additional effort to create less impact habitats is added. An example is the desalination treatment. Current desalination technologies require large amounts of energy. Desalination based on fossil fuels is neither sustainable nor economically feasible in a long-term perspective, as fuels are increasingly becoming expensive and scarce and contribute to the generation of green house gases, in addition to various pollutants and particulate matter.

* Corresponding author; E-mail: fernando.cirez@unizar.es; Telephone contact: 0034 (0) 976.76.51.84

An example of desalination of salty waters, with low energy cost, is the electrodialysis; technique based on the transport of ions through selective membranes under the influence of an electrical field. In the electrodialysis process, salt is removed from the saline water by transporting ions through membranes by means of an electric current. Saline water enters into the cell compartments, which are separated by selective membranes that are alternatively permeable to cations and to anions. When a potential difference is applied to the electrodes, an electric field is created. Cations are attracted towards the negative pole and anions towards the positive pole. Depending on the nature of the membranes, ions pass through them or are rejected. In ED the energy consumed is a function of salinity of the raw water.

Renewable and particularly solar energy offers a sustainable alternative to fossil fuels for electricity production and desalination. Solar energy potential alone has been found to exceed the total world energy demand by several orders of magnitude (the theoretical solar potential is 3,900,000 exajoules per year, some 7.000 times greater than the global primary energy demand). Solar energy generation uses local resources and may promote local business opportunities and local employment. In particular, photovoltaic (PV) provides a viable means for decentralized energy and water production in areas with abundant solar resource.

Photovoltaic, as it is well known, is the direct conversion of radiation into electricity. Non-concentrating photovoltaic systems use the direct and diffuse (global) irradiance for electricity generation, but the electricity production of solar cells can be increased by concentrating solar radiation with reflective surfaces and by using sun-tracking devices. Photovoltaic technology is modular (i.e., existing systems are expandable), has a long lifetime (manufacturers give guarantees of up to 25 years), is silent and emissions-free during its use.

Another advantage of photovoltaic systems is that they can be connected to the electrical network (grid-connected systems) or can be used in autonomous mode (off-grid systems). A number of PV modules can be connected in series (arrays) and/or parallel and the solar radiation incident on the surface of the PV modules is transformed into electric energy (direct current). In an off-grid PV system, the generated electricity is sent to batteries that are protected by a regulator for overcharging or excessive discharge. The energy stored in the batteries can be used as electrical back-up when the energetic (electrical) demand and the availability of solar hours are not simultaneous. ED due to its capacity of working with direct current is perfect to be accomplished with PV systems.

The new CIRCE building, sited in Zaragoza (Spain), has been designed as a Zero Emission Building. One of the main uses of this building is to accommodate a space to boost the development of energy efficiency and renewable energy systems integrated in buildings by the use of the edifice as an integral experiment. The own edifice integrates advanced technologies of bio-construction, energetic saving, water and materials, and renewable energies, obtaining the maximum efficiency of the available resources, without diminishing the thermal comfort. Not only the energy supply but also water consumptions have been sized following sustainable patterns and several studies are being carried out in order to satisfy them by use of renewable systems. In this way, the water consumptions, thermal and electrical loads of the building are supposed to be nearly covered by renewable generation systems as photovoltaic, solar thermal and wind turbines systems.

2. METODOLOGY

In order to analyse the behaviour of the new CIRCE Zero Emissions Building it is necessary to establish a balance between the energy and water inputs and outputs, assuming inputs as the energy production of the generation systems and phreatic water and outputs as the energy requirements to feed the electric devices and the water to cover consumptions.

In this paper, at 2.1 section, an brief description of CIRCE building is shown. In 2.2 section, the final energy and water consumptions due to the intrinsic uses of the building will be estimated. In 2.3 section, several photovoltaic systems (accomplished with pumping and ED) will be analyzed to obtain the water needs. Finally, once the water consumptions are covered and the energy production from renewable systems is known, the CIRCE building will be evaluated as Zero Emissions Building.

2.1 The new CIRCE building description

The building CIRCE shown in figure 1 is located in the Technological Campus Rio Ebro of the University of Zaragoza. The project of the building has been elaborated by the equipment of architects directed by Petra Jebens – Zirke, as a singular and exemplary building, a model of bio-construction and sustainability and a portal to the last technological advances as for eco-efficiency.

The building is compactly projected and divided in two plants where three different elements can be identify: the round core with the dome, the offices grouped around it and the laboratories. The laboratories constitute a rectangular plant with azimuth 36 degrees on the east-west axis, which acts as barrier against the predominant wind. This help to avoid the considerable decreases of temperature not wished in the cold months. In addition, it also exists a solar chimney that helps to the building to take advantage of these dominant winds to naturally refresh the building during the summer period.

The covers of the building are projected as gardens, shaping a biologic habitat of autochthonous plants, resistant to the climatologic characteristics and with minimal needs of irrigation. The vegetable roofs constitute an ecological and economic very profitable option: they compensate the occupation of free surfaces, generate oxygen, act of thermal and acoustic isolation and help to the absorption of particles of pollution and dirt. Moreover vegetable roofs help to avoid the overheating and reduce the extreme oscillations of temperatures and the dampness.

As a Zero Emissions Building the presence of renewable energy systems is a duty. Photovoltaic, solar thermal, wind turbine and geothermal are the expected renewable generation systems to be implanted to contribute to the energy requirements.

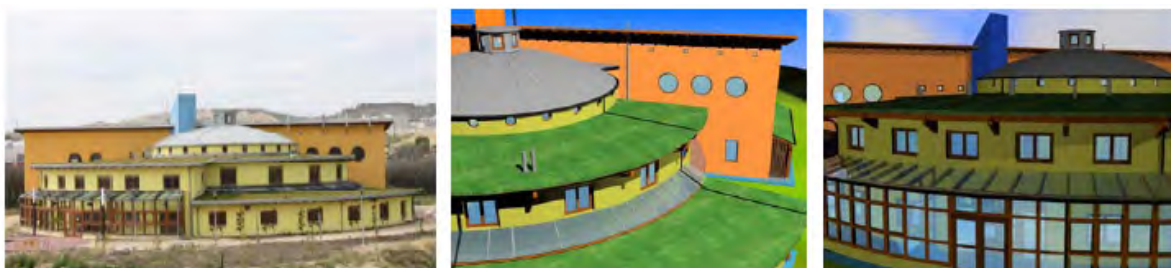


Figure 1. Overall view (left), green roof detail (center) and solar chimney detail (right)

2.2 Energy and water demands in the building

According to the Spanish “Technical Building Code” all the new buildings must obey some energetic requirements. In order to carry out the calculations for demands and isolations, the Spanish Department of Housing provides two sizing software tools, *Lider* and *Calener*, to help in this task.

The heating demands in the building were calculated by means of the *Lider* application, resulting 38.5 kWh/(m²·year) for heating and 11.8 kWh/(m²·year) for cooling as presented Zabalza (2010). Taking into account, to the evaluate the energy consumptions, a 75 W/person gain for sensitive heat and 55 W/person gain for latent heat, 15 W/m² gain for computers and similar devices, 12 W/m² gain for inside illumination and 8-10 working hours/day, the final energy consumption associated with pumps and fan

coils, provided by the application *Calener*, has been joined to the consumptions of heating and refrigeration obtained, with the following distribution: heating (67%) and refrigeration (33%).

As a summary, the table 1 shows all the energy consumptions considered in the analysis. Attending to the energy source, the allocation is natural gas for the heating boiler 44% and the remaining 56% to electricity.

	kWh/(m ² ·year)	MWh/year	MWh/lifecycle
Heating	21.56	47.86	2,393
Refrigeration	4.38	7.68	384
Hot water	0.09	0.15	8.5
Illumination	13.78	24.13	1,206.5
TOTAL	45.58	79.82	3992

Table 1. Final energy consumptions of the CIRCE building.

To calculate the building water demand it has been assumed a daily use of fifty times for urinary and wash basins, the use of five minutes per shower and two hundred uses for bowl, following a local study carried out by Fundación Ecología y Desarrollo, (2003).

The building, framed within the tertiary sector (offices and laboratories) counts with 16 bowls, 2 showers, 4 urinary, 16 wash basins and an occupation of 65 persons for 335 days/year. In addition it has been also computed the irrigation of the garden and green roofs during the half of the year and in this period one time every two days. The results of the total consumption are shown in table 2.

	Quantity	Flow Capacity	or Daily frequency	Daily consumption (l/day)	Year consumption (m ³ /year)
Bowl	16	9 l	1 use/200 per	46.8	15.7
Shower	2	10 l/min	1 use/day; 5 min/use	50	16.8
Urinary	4	9 l/min	1 use/50 per; 5 s/use	3.9	1.3
Wash basin	16	9 l/min	1 use/50 per; 16 s/use	49.92	16.7
Gardens (m ²)	500	5 l/(m ² ·day)	1 use/2days	1,250	456.3
			TOTAL	1,400.62	506.8

Table 2. Final water consumptions of the CIRCE building

2.3. Photovoltaic energy systems to feed water pumping and water treatment

As previously stated and although the building has the possibility of being connected to the city supply water network, one of the objectives of this study is to consider the provision of the water requirements from water reuse and groundwater.

As mentioned, there are two principal needs of water: irrigation water and domestic house water (DHW). In this section, the possibility of arranging PV modules to several systems to cover these needs is presented.

2.3.1 Irrigation of garden and green roofs powered by photovoltaic

As previously stated, the irrigation of the garden and green covers rises up 1.25 m³ per irrigation day (April to October). Due to the proximity of the Ebro River to the building location, there are several flows of groundwater at 8 – 10 meters depth. The amount of available water is enough to satisfy the estimated demand.

Once the quantity is enough to satisfy the demand, the next step in the study faces it quality. According to the Environmental Department of Spain analytical results report

(2006), the groundwater that flows under the building fulfils to the regulations for irrigation water, so it was only necessary to design a system to pump the water.

In particular a photovoltaic system directly connected to a direct current pump to elevate from underground to a tank has been sized. An auxiliary battery system could be necessary for the months as April or October. An diagram of the system is illustrated in figure 2:

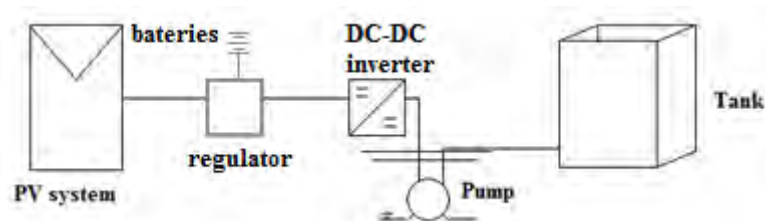


Figure 2. Diagram of the PV pumping irrigation system.

In order to size the system the following considerations were taken: the volume of the tank should cover irrigation and DHW for two days (that is 3 m³), the tank is located at the laboratories roof (20 m of height), the batteries must have four days of autonomy and 5% of load losses probability and the pumping operation is limited to 10 – 14 hours. The tilt of modules is 30° in order to obtain the most available energy for April which is the worst month in terms of radiation and precipitations.

In a first step the hydraulic energy was calculated:

$$\text{Hydraulic energy} = V \cdot h \cdot \rho \cdot g \quad (1)$$

The energy required, worked out from the eq. 1, will be 0.1632 kWh/day. As during the months between November and March it is no necessary to irrigate the grass, the pumping electricity needs to cover the water supply for two days (150 l/day) drop to 0.0082 kWh/day. An excess, no more than 10% of the above quantity, of net energy will be required due to the hydraulic losses in elbows and friction in pipes. In addition the efficiency of the pump must be taken into consideration.

The PV system configuration that cover the energy and water withdrawals, after using commercial application *PVSYST*, oriented to the photovoltaic system analysis consists of one Solibro CIGS SL-1-75 module, one 30Ah PVX340T Concorde battery and one floating Grundfos SQF 2,5 pump.

2.3.2 Water consumption production by means of electrodialysis powered by photovoltaic

An electrodialysis system to produce drinking and domestic hot water can be powered by a photovoltaic installation. It is due to the ED systems works with direct current.

A pilot electrodialysis plant, EUR2B-10P, has been acquired in order to proceed with several experiments as using batteries or directly connect the pilot plant to the PV modules, analyzing the capacity and batch time of the electrodialyzer or choosing different current intensity or voltage conditions. In all of these variations, the water consumptions should be covered searching the optimal conditions that cause the minimum energy load.

As mentioned, the storage tank of pumped water was oversized to satisfy the supply of water for two days. But the physicochemical characteristics of the water stored in the tank, similar to phreatic water, could not be adapted for the human consumption.

Some of these characteristics, such as conductivity, concentration of chlorides and water hardness, were reported by the Spanish Environmental Department and appear in the figure 3:

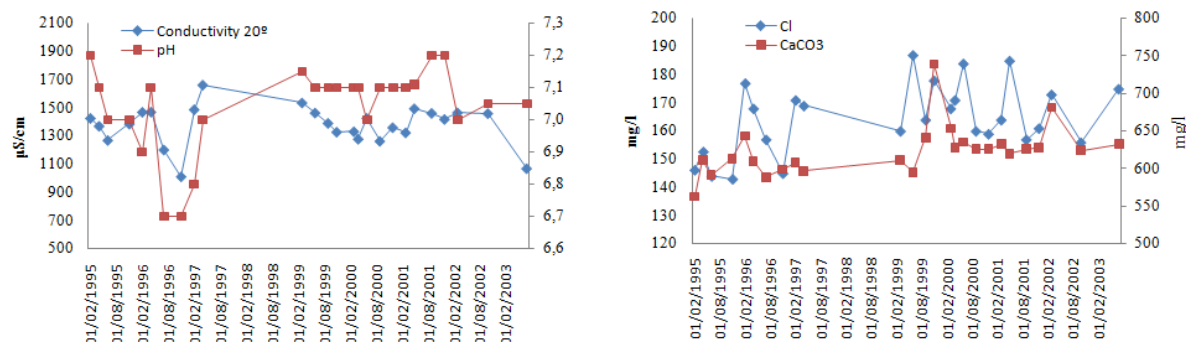


Figure 3. Conductivity, pH, Cl concentration and water hardness evolution of CIRCE phreatic water flow.

This report, carried out during eight years, shows an average conductivity, pH, concentration of chlorides and water hardness values of 1,378 $\mu\text{S}/\text{cm}$, 7.04, 164.4 mg/l y 623.76 mg/l respectively.

The World Health Organization (WHO) establishes as drinking level for consume values as 500 and 2,500 $\mu\text{S}/\text{cm}$ for conductivity, between 6.5 and 8.5 for pH, 250 mg/l as maximum chlorides concentration and between 100 and 500 mg/l for water hardness. As it can be seen groundwater obeys all the requirements (shown in figure 2 and regulated by WHO) with the water hardness, calcium and magnesium concentration exception. Due to the high alkalinity of building location grounds whereas the water flows, the concentration of these substances go beyond the maximum limits and the water should be treated.

For waters with relatively low salt concentrations (less than 5,000 ppm), electrodialysis is generally the most economic process in comparison to others technologies as reverse osmosis.

This technique has proved its feasibility and high performance in the desalination of brackish water, when the required salinity of the produced water is of the order of 500 ppm.

As previously mentioned the combination of PV and ED is attractive because ED requires a direct current (dc) power supply as the driving force for removing the salt ions, that is why an inverter DC/AC and the consequently energy losses in the transformation is not necessary. These systems are appropriate for small applications in isolated locations where continuous fresh water production is not needed and the volume of daily treated required water is small (about 1–10 m^3).

Two possible alternatives have been studied: the first one an ED pilot plant directly connected with photovoltaic and the second one with the presence of batteries. In both cases it will be necessary a second tank where the treated water could be stored for its distribution. This tank has been sized in order to supply two days what supposes a capacity of 300 liters.

2.3.2.1 Electrodialysis combined with photovoltaic systems:

In a PV-ED system without batteries, due to the fact that the electrodyalizer is directly connected to the PV panels, the process is sensitive to variations on solar irradiation. From experimental results shown in Ortiz et al study (2007), it can be established that the desalination of brackish water using a system of electrodialysis powered by photovoltaic energy can be successfully carried out at different meteorological conditions. The process has an easy start-up and shut-down of the process for intermittent operation. But the applied cell voltage is a critical operating condition in electrodialysis processes as the voltage determines the current in the cell and hence the desalination efficiency as well as energy consumption. Besides, with the direct connection of the electrodialysis unit to the panels, the operating point of the PV generator can be located far from the maximum power point, with a low efficiency in the conversion

solar/electricity. Several changes in the configuration of PV modules are proposed to use during the desalination process (all the PV modules in parallel in the first stages, all the modules in series at the end, and other configurations in the intermediate stages) in order to obtain a better drinking water production per m^2 of solar panel.

As previously stated, the building demand of water is 150 l/day. The ED pilot plant operates at a nominal flow rate of 180 l/h and for the needs the average time at nominal operation conditions is four hours. According with Fritzmann et al., (2007); Uche, (2000); and Uche et al., (2006) studies the estimated consume energy will be 1 kWh/m^3 .

A possible designed system could consist in two Solibro SL1-75 CGIS modules with a tilt of 30° south oriented directly connected to the ED pilot plant rectifier. The estimated production of these modules according to the *PVSYST* simulations is 161 kWh/year and the energy needs of the pilot plant is 93.1 kWh/years . But even with a 68 kWh/year of excess production the absence of batteries implies that in case of several cloudy days or even in winter season the supply of consume and sanitary water it is not secured and that it will be necessary to connect the ED pilot plant to the grid connection of the building.

In a PV-ED system with batteries, the supply problem due to the accumulation of several cloudy days it is not present and the electrodialysis process system becomes insensitive to variations on solar irradiation. In addition when batteries are used it is not necessary to treat all the water in four hours and it is possible to search whether the batch time is another variable that can be optimized in order to decrease the energy requirements. On the other hand the systems become more costly due to the increase of the final price for the batteries introduction.

When batteries are used three additional variables should be optimized: the number of autonomy days, the probability of losses of load and the time of use of the pilot plant.

A designed system could consist of three solibro SL1-75 CGIS modules with a tilt of 50° south oriented connected to two PVX-340T Concorde batteries. According to the *PVSYST* simulations, with this system the supply of water is secured for 3 days of autonomy, 5% of losses of load probability and a use of the pilot plant from 10 to 15 hours.

2.3.3 Analysis of the photovoltaic system

An optimized system would be a unique photovoltaic installation that by the use of switches could feed the energy requirements for water and in addition contributes to the energy requirements of the building. With these switches an automatism system could prioritize the supply of energy loads for pumping and electrodialysis and when the needs of water are covered could inject the electric production from PV modules into the grid of the building.

For the circular section of the building a layout has been studied where the photovoltaic modules are superposed on the cover's surface. Even though the ideal inclination for the location would be 30 degrees one instead of the surface inclination (3 degrees), with this inclination the photovoltaic generator is imperceptible in a visual way. The photovoltaic installation consists in 32 photovoltaic modules Solibro CGIS SL1-75 resulting in a 2 kW (2.4 kWp) array. This array is made up of eight parallel strings each one consisting of four modules in serial and is plugged to a Power One PVI 2000 OUTD AC-DC inverter.

For the laboratories plant of the building, a PV installation has been sized where the photovoltaic modules are inclined by means of structural supports on the cover surface and orientated to south direction with an inclination of 30 degrees, instead of following the structural axis of the plant. Thus compensates the less recommended orientation of the plant with the more suitable orientation and inclination.

The studied installation consists of four photovoltaic arrays of 32 modules arranged in 4 strings of 8 modules in serial with an inclination of 30° , with a south perfect orientation and a separation in south direction between generators of 8.0 meters. This installation results in 8 kW plugged to a SMA Sunny mini central 8000 TL AC-DC inverter.

According to the simulations made with *PVSYST* and the meteorological information obtained with *METEONORM*, the annual production of the PV system is expected of being 16,634 kWh/year. A 3D simulation of the CIRCE building with the mentioned photovoltaic installations is shown in figure 4.

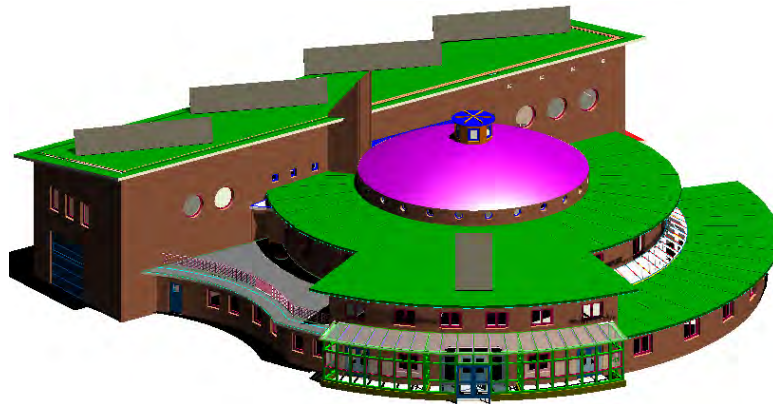


Figure 4. 3D simulation of the PV installation (10 kW) integrated in the CIRCE building.

2.5. Other renewable energy generation systems integrated in the building.

Due to the fact that Zaragoza presents good meteorological conditions with regard to the installation of wind power systems, the possibility of introducing in the bordering areas to the building a wind turbine Aeinclin 6000 of 6 kW was studied.

The wind generator will be mounted in a tower to a height of 20 meter. Its rotor is formed by 3 blades of fiber of glass / carbon of 4 m of diameter. The electrical generator is a three-phase alternator of permanent magnets of neodymium.

According to the simulations made with the commercial application *WASP*, oriented to the wind system analysis and the meteorological information, the annual production of the PV system is expected to be 13,465 kWh/year.

In figure 5 it can be seen a simple diagram that involves all the renewable electric generation systems and their uses in the CIRCE Building. As it observed the 2 kW photovoltaic installation feeds the pumping and electrodialysis energy demands and when these consumptions are covered the switch allows injecting the rest of energy produced into the building. The 8 kW photovoltaic installation and the 6 kW wind turbine are directly plugged to the building. In addition the building is also connected to the grid connection of the city system.

It has been also studied the possibility of installing thermal solar power as a method of reducing the use of fuel in the boiler. The possibility of installing four vacuum tube solar collectors, Vitosol 200, to cover part of the demand of heating of the building was considered. These collectors consist of 30 vacuum pipes and by the calculations worked out from their linearized equation of performance it is observed a maximum performance of 74 % and a linear coefficient of losses of 1.06 W/m²K.

Because the solar thermal system contributes only to the consumption of heating, the using period is between October and April. When this period of the year is over, to avoid the possible breaks provoked by overheating, the primary circuit of the solar system will be empty.

Applying the f-chart methodology, it has been calculated that the four vacuum tube solar collectors might cover 3,702 kWh thermal/year.

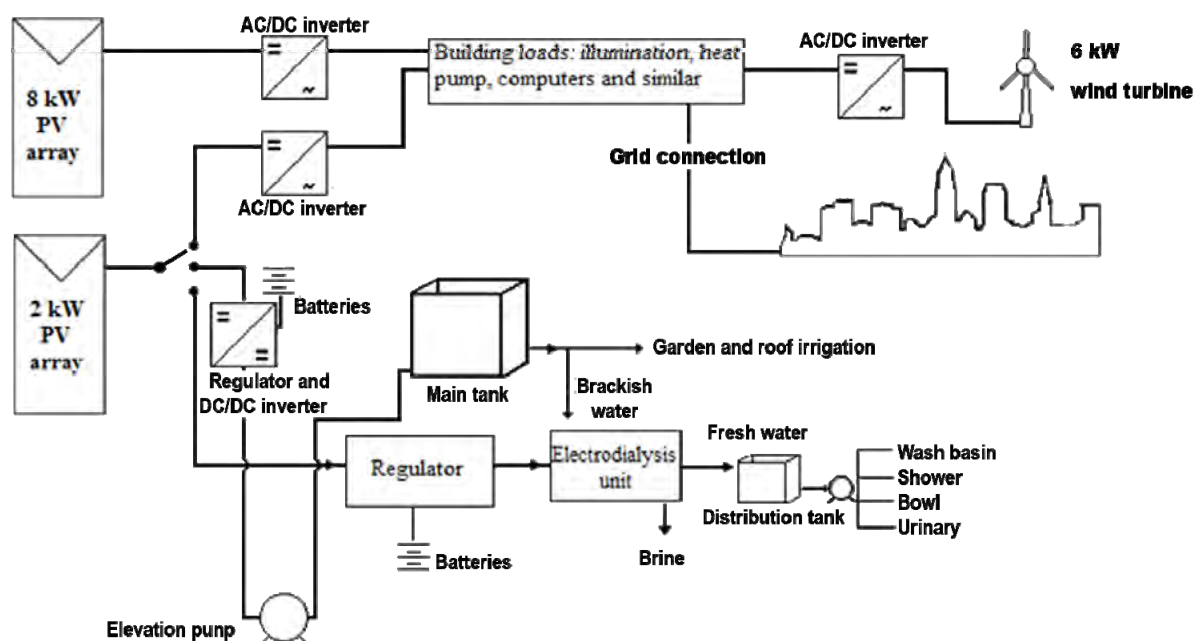


Figure 5. Photovoltaic and wind turbine generation system integrated on CIRCE building.

3. ENERGY AND WATER BALANCES

After being estimated the water and energy consumptions and the generation of energy from renewable systems it is necessary to realize the balance to the building to analyze the degree of coverage of its needs.

With regard to the water consumption, between April to October, the major needs of water result in a daily consumption of 1.4 m³ (irrigation plus domestic house water). Between November to March, the irrigation is not necessary and only 150 l/day of water are needed.

All the consumptions of water of the CIRCE building would be supplied thanks to the groundwater. This water will be pumped, stored and subsequently treated.

Regarding the electric balance, the annual needs have been estimated in 58.61 MWh/year (56% of heating plus refrigeration and illumination). The annual generation of electricity by means of renewable systems is the photovoltaic production (once the ED+pumping energy are discounted, 0.13 MWh/year) plus the wind turbine production. The result of this addition is 29.97 MWh/year.

It can be seen an electric unbalance of 28.64 MWh/year that the building should take from the grid connection of the distribution city system.

In the thermal balance, the annual needs result in 21.06 MWh/year. The vacuum tube solar collectors, as was analyzed, are only capable to produce 3.7 MWh/year. This fact results on a thermal unbalance of 17.35 MWh/year that should be covered by the boiler.

4. CONCLUSIONS

It can be observed how by means of ED use with supply of renewable energies as photovoltaic, is possible to cover the consumption needs of a building in terms of water and irrigation. The optimization of this system (batch time, battery capacity and feed flow) is required to decrease the energy supply.

Up to the present, the CIRCE building it has not still reached a Zero Emissions Building qualification. There will be studied the possibility of adding major quantities of renewable energies for the electrical production so that the 28.64 MWh remaining are

covered. In terms of photovoltaic power, with a 20 kW installation the rest of energy needs will result satisfied.

Regarding the coverage of the thermal unbalance, a biomass boiler is going to be added so the gas demand will decrease.

REFERENCES

- Wang, L., Gwilliam, J. and Jones, P., 2009. "Case study of zero energy house design in UK". *Energy and buildings* 41. Pp. 1215-1222.
- Hernández, P. and Kenny, P., 2010. "From net energy to zero emissions building: Defining the cycle zero energy buildings (LC-ZEB)". *Energy and buildings* 42. Pp. 815-821.
- LIDER and CALENER 2009. Software package, Ver. 3.0. Industry, Tourism and Commerce Department of Spain.
- Zabalza, I. 2010. *Life cycle assessment in buildings: Methodology, applications and possible simplifications*. Doctoral dissertation. Department of Mechanical Engineering. University of Zaragoza.
- Fundación Ecología y Desarrollo, ECODES, 2003. *Buenas prácticas para el desarrollo sostenible*.
- Confederación Hidrográfica del Ebro, 2006. *Real Average Values for tap-water in Zaragoza*. http://chebro.redesquimsubter.info/ficha_redes.php?ipa=281510027. Confederación Hidrográfica del Ebro.
- Ortiz, J.M., Expósito, E., Gallud, F., García, V., Montiel, V. and Aldaz, A., 2007. "Electrodialysis of brackish water powered by photovoltaic next term energy without batteries: direct connection behavior". *Desalination* 208. Pp. 89-100
- Fritzmam, C.; Lowenberg, J.; Wintgens, T. and Melin, T. 2007. "State of the art of reverse osmosis desalination". *Desalination*, 216 pp.1-76. Elsevier.
- Uche-Marcuello, J. 2000. *Thermoeconomic Analysis and Simulation of a Combined Power and Desalination Plant*. Doctoral dissertation. Department of Mechanical Engineering. University of Zaragoza.
- Uche, J.; Valero, A. and Serra, L. 2006. "Potential paper of desalination. Water Crisis: Myth or Reality?" In Rogers, P. and Llamas, R. (Eds.), Harvard University, USA. Taylor & Francis.
- PVSYST, Study of Photovoltaic Systems, 2009, Software Package, Ver. 5.05, University of Geneva, Switzerland.
- METEONORM, *Global Meteorological Database for Engineers, Planners and Education*, 2007, Software Package, Ver. 6.02, Meteotest, Bern, Switzerland.
- WASP, *the Wind Atlas Analysis and Application Program*. 2010, Software Package, Ver. 10, Riso DTU, Denmark.

SIMULATION AND APPLICATION OF A DC ENERGY DISTRIBUTION SYSTEM FOR HYBRID RENEWABLE ENERGY SYSTEMS

*Engin Cetina^{*1}, Ahmet Yilancia¹, Harun Kemal Ozturka¹, Mahmut Hekima¹,
Ismail Kasikcib², Metin Colakc³, Siddik Iclic³*

¹ *Energy Research&Application Center, Pamukkale University, Kinikli, 20070,
Denizli-Turkey*

² *Electrotechnic Department, Biberach University of Applied Sciences,
Biberach–Germany*

³ *Solar Energy Institute, Ege University, Bornova, 35100, Izmir–Turkey*

ABSTRACT

Hybrid renewable energy systems are the systems where the renewable energy sources as wind, hydrogen, solar etc. have been utilized simultaneously. In the recent years, the increase in the petroleum prices, the rapid run out tendency of fossil fuel reserves and their inavoidable harmful effects and political instabilities in the regions of energy sources have been accelerated the studies on the renewable energy systems. The electrical energy produced by renewable energy systems like photovoltaic panels and fuel cells is in the form of the direct current (DC) electrical energy. In effect, despite of the fact that the electrical energy produced by the wind turbines is in the form of alternative current (AC) in proportion to the wind speed, this AC energy is converted into the DC energy by the internal converters in the low-scale wind turbines used in the buildings and then the network is supplied by this DC energy. Thus, the DC energy produced by photovoltaic panels, fuel cells and wind turbines has to be converted into AC energy due to the fact that the consumers need generally AC electricity. Such a DC/AC conversion brings some disadvantages such as the need of a DC/AC converter, the involvement of some harmonics, the loss of energy, the increase in dimension and cost, and some degradation of the quality of the energy. Transmission of electrical energy from production place to consumption place faces with the problem of energy loss. The energy produced by photovoltaic panels, fuel cells and wind turbines is in the form of DC and thus we can abstain from the above mentioned problems if we use DC loads without a DC/AC conversion. In this study, firstly, a Matlab© simulation software is created for DC hybrid system and then, its application, in which the DC energy produced by RHESs is consumed by the DC loads (44 compact flurescent lamps, circulation pump, freezer/refrigerator, vacuum cleaner, TV and 2 fans) without being converted into the AC form, has been presented. For this purpose, a DC energy distribution unit is established for the photovoltaic-wind-fuel cell hybrid energy system existing at Pamukkale University, Denizli, Turkey.

Keywords: DC Energy Distribution, Matlab©, Photovoltaic, Fuel Cell, Wind Turbine

1. INTRODUCTION

Conventional fossil fuel sources like coal, oil, natural gas have recently entered into a quick decreasing tendency. In addition, with the use of such fossil fuel sources, it is inevitable that they contaminate the nature, cause global warming by forming greenhouse effect and therefore take our world into an undesirable disaster. Therefore alternative and renewable energy sources have importance more than before in the human history (Oner et al., 2009). That the present energy production sources enter quickly into the exhaustion tendency, that raw material prices increase, their negative effects on the environment and human health, some difficulties in the usage have increased the studies made on new and renewable energy sources (Cetin et al., 2001).

* Corresponding author; E-mail: engincetin@pau.edu.tr; Tel.: 0090-258-2963747

Distribution of electrical energy from production location to another consumption location also brings some energy losses. In power distribution systems, Alternative-Current (AC) distribution technology is used generally. Distribution of electrical energy produced by Hybrid Renewable Energy Systems (HRES) with minimum losses is very crucial since these systems are costly and their intermittent production nature. Power factor exists in AC energy distribution and affects the distributed active power unfavorably. In Direct Current (DC) energy distribution, there is no energy losses like above since power factor is 1. For the same conductor, DC voltage distributes more power than AC voltage. Voltage control in AC distribution has some problems if line capacity and inductive voltage drop are considered. In AC energy distribution, there are some problems which exist in DC energy distribution less than AC energy distribution such as voltage oscillation, active losses, stability problems, limitations in current carriage capacity, line interactions, frequency effects, voltage drops, power plant expenses etc. Nowadays, although AC energy has these problems, it is widely used because conventional power stations like hydroelectric, natural gas have alternators and available appropriate AC devices for usage. However, energy produced by photovoltaics, fuel cell systems and wind turbines (with internal DC/DC converter) is DC, and also in case of DC loads usage, DC/AC conversion is not needed. This eliminates the problems mentioned above (Cetin et al., 2010a).

In this study, it is aimed to distribute electricity in DC form and also to be planned to carry out R&D activities by using in loads which have DC characteristics. For this purpose, photovoltaics-wind turbine-fuel cell system, DC loads, and DC distribution mechanism were examined experimentally in Pamukkale University Clean Energy House.

2. RENEWABLE HYBRID ENERGY SYSTEM

The photovoltaic–wind turbine–fuel cell hybrid energy system established at Clean Energy House (CEH) includes 5 kW photovoltaic panels group, two 1.2 kW fuel cells and two 400W wind turbines (Cetin et al., 2010b). The aim was to design a unique, integrated system for the house, using only solar energy to meet all energy needs (with no inputs from fossil based energy sources) and to provide an environmentally benign design and operation (Cetin et al., 2009). The photovoltaic panel group constitutes the primary energy supplier of the system, while fuel cells and wind turbines are the secondary suppliers since the area is not windy through the year except for in the winters. Therefore, wind turbines assist in charging the batteries during the period when the solar energy is not enough (Cetin et al., 2010b). In Fig. 1, the CEH is illustrated (Cetin et al., 2010a).

Each of the photovoltaic panels is Kyocera 125GHT-2: the output power is 125 W, the material is polycrystalline, the maximum output voltage is 17.4 V, and the maximum output current is 7.2 A, the open-circuit voltage is 21.7 V, the short-circuit current is 8.0A (Kyocera, 2009). Fig. 2 illustrates the fixed and mobile photovoltaic panel groups (Cetin et al., 2010b).

The fuel cells shown in Fig. 3 are used to produce electrical energy from the hydrogen stored in the system. The PEM-type fuel cells are adopted due to their simplicity, compactness and easiness to-maintenance (Cetin et al., 2010b). Each of the Nexa™ fuel cell modules produces maximum 1.2 kW DC energy and has a 22–50 V DC nominal output voltage. The Nexa™ power module provides up to 1.2 kW of unregulated DC power at a nominal output voltage of 26 V DC. The fuel cell stack consists of 47 sandwiched fuel cell elements (Nexa, 2003).



Fig. 1. Clean Energy House (CEH).



Fig. 2. The fixed and mobile photovoltaic panel groups.

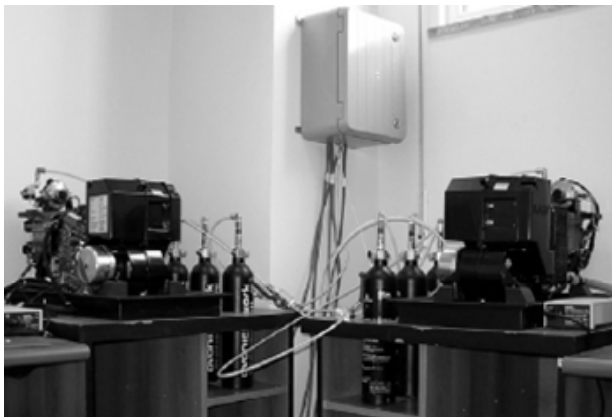


Fig. 3. Fuel cell units.



Fig. 4. Wind turbine.

The system also includes 2x400 Wp wind turbines which are chosen in accordance with the 48 V DC system as shown in Fig. 4. The Air-x™ model turbine is of 1.17 m rotor diameter and its power is 400 W. The range of wind speed for the turbine to be able to produce electrical energy is between 3.58 m/s (cut-in speed) and 12.5 m/s (cut-out speed) (Air-x, 2008).

3. MATLAB-SIMULINK® MODEL OF DC SYSTEM

Before the construction of the DC system, Matlab® simulation was examined. In Fig. 5, Matlab-Simulink® model of DC system is illustrated (Cetin, 2010).

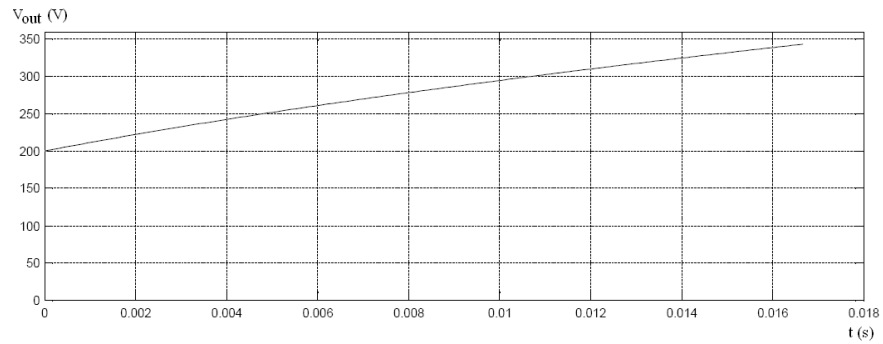


Fig. 6. DC/DC converter output voltage waveform from Matlab-Simulink[®] model.

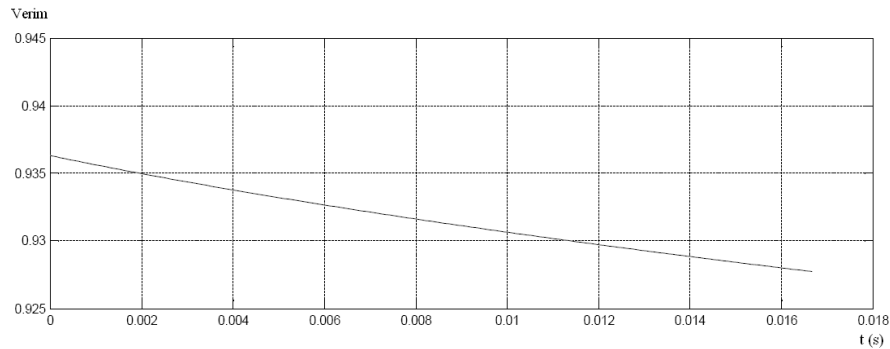


Fig. 7. DC/DC converter efficiency curve from Matlab-Simulink[®] model.

4. CONSTRUCTION OF DC SYSTEM

In DC system, there are 12 V (44 fluorescent lamps, TV, and vacuum-cleaner) and 24 V (freezer-refrigerator, circulation pump, and 2 fans) DC loads (Fig. 8). The total load power is 735 W. Electrical properties of load units are shown in Tab. 1 (Cetin et al., 2010b).

Tab. 1. Devices used in the experimental study and their electrical properties.

DC load	Nominal voltage (V)	Nominal current (A)	Power (W)
19" LCD TV	12	3.80	45
Vacuum cleaner	12	3.00	36
Compact fluorescent lamp	12	0.92	11
Circulation pump	24	2.92	70
Fan	24	0.60	15
Freezer/refrigerator	24	2.91	70

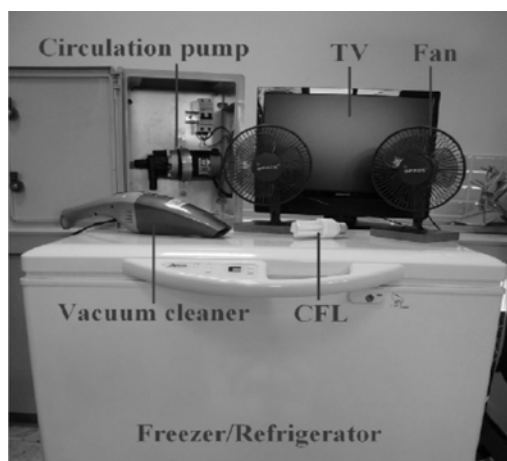


Fig. 8. DC load units.

In Fig. 9, a DC distribution power box unit, which is composed of five main units as described below, is illustrated: Unit 1 has connectors and distribution bars (Fig. 9, sections A and B respectively) for 12 V and 24 V DC power distribution and DC surge protector (Fig. 9, section C). Unit 2 has 12 V and 24 V DC/DC converter devices (Fig. 9, section D). Unit 3 has DC circuit breakers, DC insulation monitoring device against faults between positive/negative line and earth protection line (Fig. 9, section E). Unit 4 has PLC CPU unit, its analog modules for voltage and current data acquisition (Fig. 9, section G) and PLC power supply module (Fig. 9, section F). Unit 5 has voltage signal converters and shunt devices to convert analog voltage and current signals to digital form (Fig. 9, section H) (Cetin et al., 2010b).



Fig. 9. DC power distribution box.

In the system, circuit breakers are used for protection. Having 12 V and 24 V DC voltage levels of energy distribution is itself a matter of safety for the habitants and the devices, for the critical voltage level for human is 120 V DC (Kasikci, 2008). The system has also a RIR48N Contrel Elettronica insulation monitoring device. This device protects the system by switching off the circuit in the case of a grounding fault for instance positive pole-ground or negative poleground contact (Cetin et al., 2010b; Contrel, 2009).

In the main power distribution panel of the system, a DC surge protector is employed to prevent the possible damages of the voltage pulses stemming from PV/wind turbine group or fuel cell. The surge protector can operate up to 60 V DC, and its maximum operating voltage is 130 V, its nominal current is 26 A, its short-circuit switch-off capacity is nominally 2.5 kA and maximum 6.5 kA (Cetin et al., 2010b; Siemens, 2009).

5. EXPERIMENTAL STUDY

For the analysis of the DC distribution system, a Fluke-43B power quality analyzer is used. Fluke-43B is a device that can analyze AC and DC power, voltage, current and energy. For DC current measurements, the Hall-effect 100 A DC probe of the device is used (Cetin et al., 2010b).

Fluke-43B can make the measurements on any points on the DC distribution panel. Fig. 10 shows voltage and current signals from the input of 12 V converter when all 12 V loads (CFLs, TV and vacuum cleaner) in charge are switched on. As can be seen from the figure, the input voltage of the converter is 47.81 V and the input current is 14.31A. Fig. 11 shows the voltage and current signals read from the output of the 12 V converter when all

of the 12V loads (CFLs, TV and vacuum cleaner) are switched on. As can be seen from the figure, the output voltage of the converter is 12.29 V and the output current is 46.91A (Cetin et al., 2010a).

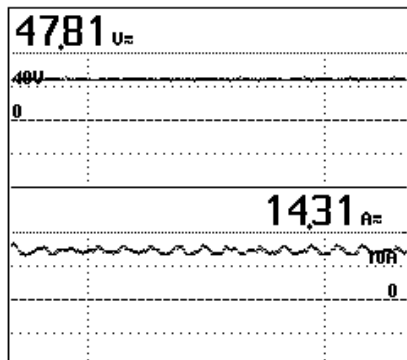


Fig. 10. Voltage and current signals from input of 12 V converter when all loads in charge.

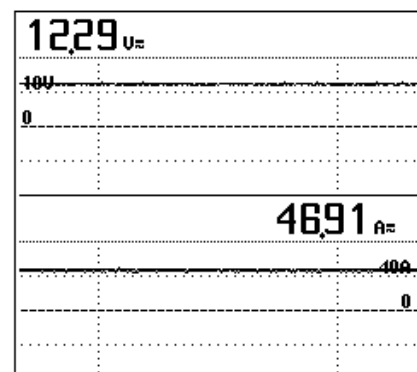


Fig. 11. Voltage and current signals from output of 12 V converter when all loads in charge.

Fig. 12 shows the voltage and current signals read from the input of the 24 V converter when circulation pump and 2 fans are switched on. As can be seen from the figure, the input voltage of the converter is 47.53V and the output current is 2.560 A. Fig. 13 shows the voltage and current signals read from the output of the 24 V converter when circulation pump and 2 fans are switched on. As can be seen from the figure, the output voltage of the converter is 24.31 V and the output current is 3.586 A (Cetin et al., 2010a).

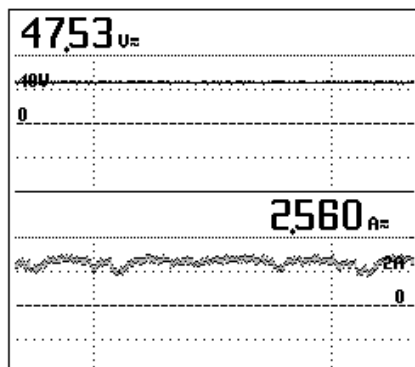


Fig. 12. Voltage and current signals for 24V converter input when pump and fans are switched on.

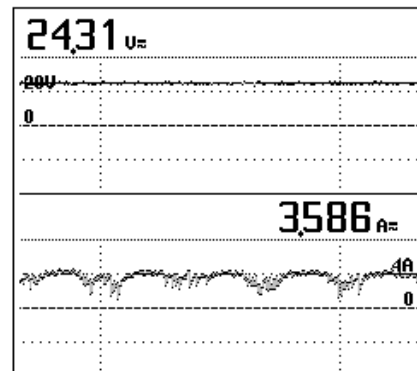


Figure 13. Voltage and current signals from 24V converter output when the fans and the circulation pump are activated.

For fuel cell applications, an emergency situation is described. In an emergency situation only selected loads (e.g. 20 DC lamps, TV, 2 fans, freezer/refrigerator) are supplied by fuel cells. These situations are actualized in no power situation from PV module and/or wind turbine.

Figure 14 shows the voltage and current signals from the output of the fuel cell when all loads in charge are switched on. As can be seen from the figure, the output voltage of the fuel cell is 30.63 V and the output current is 16.05 A (Cetin et al., 2010c).

Figure 15 shows the power values with voltage and current signals read from the output of the fuel cell when all loads are switched on. As can be seen from the figure, the active output power of the fuel cell is 492 W, reactive power is 13 VAR and apparent power is 492 VA (Cetin et al., 2010c).

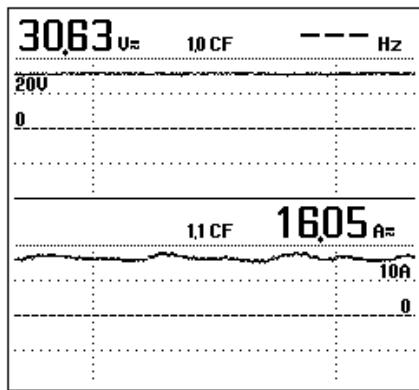


Fig. 14. Voltage and current signals from output of the fuel cell when all loads in charge.

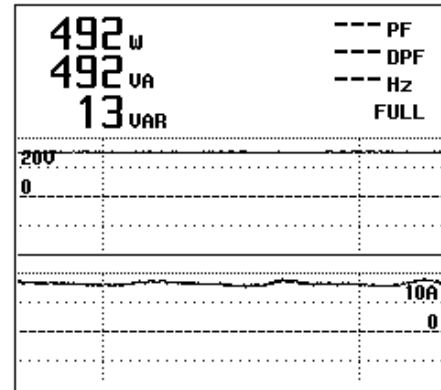


Fig. 15. Power values with voltage and current signals from output of the fuel cell when all loads in charge.

6. CONCLUSION

In this study, a DC power distribution system with a hybrid renewable energy system in Denizli, Turkey, in terms of DC power distribution, DC loads, system simulation, and etc., is performed. In addition, some measurements such as voltage, current, and power are measured to obtain the electrical characteristics of the system.

Photovoltaic panel, wind turbine and fuel cell systems produce Direct Current (DC) electrical energy. Therefore, DC electrical energy produced by photovoltaics, fuel cell systems and wind turbines has to be converted to Alternative Current (AC) due to AC demands of consumer. This DC/AC conversion causes cost increase (additional DC/AC inverter), energy losses, increase in system size and deterioration of energy quality.

In this study, a photovoltaic-wind turbine-fuel cell hybrid energy system was examined. A micro DC power distribution system which has 12 V / 565 W DC loads and 24 V / 170 W DC loads was constructed. On this system, several electrical experiments were examined. Experimental outputs and Matlab® simulations were compared.

From the obtained electrical construction of whole system, it can be said that the DC power distribution is suitable for hybrid renewable energy systems. In the residence, 12 V and 24 V voltages have been used for safer conditions i.e. not only for inhabitants but also the devices in the residence. The need for AC conversion is overcome by distributing and consuming the DC energy in a DC manner. The DC distribution eliminates the cost of conversion, the electrical losses during conversion and also the need for some space required by the inverter.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the Scientific Research Projects Council of Pamukkale University (project no: 2010KKP119), Turkish State Planning Organization (DPT), the Scientific and Technological Research Council of Turkey (TUBITAK), Bereket Energy Inc. (Turkey), Kaelsa Heating Systems Industry (Turkey), Siemens (Turkey) and Contrel Elettronica (Italy).

REFERENCES

Air-x Owner's Manuel PDF Version, 2008, <http://www.windenergy.com>.

- Cetin, E., 2010, *Design, application and analysis of a direct-current distribution grid for a photovoltaic-wind-fuel cell hybrid energy system*, Ph. D. Thesis, Ege University Solar Energy Institute, 183 p.
- Cetin, E., Yilanci, A., Ozturk, H. K., Hekim, M., Kasikci, I., Colak, M., and Icli, S., 2010a, "Investigation of DC and AC power distribution systems for renewable energy applications", *5th International Ege Energy Symposium & Exhibition, June 27-30, Denizli-TR*.
- Cetin, E., Yilanci, A., Ozturk, H. K., Colak, M., Kasikci, I., and Iplikci, S., 2010b, "A micro DC power distribution system for a residential application energized by photovoltaic-wind/fuel cell hybrid energy systems", *Energy&Buildings*, 42 (8), 1344-1352.
- Cetin, E., Yilanci, A., Ozturk, H. K., Kasikci, I., Colak, M., and Icli, S., 2010c, "A Sample DC power distribution system for fuel cell applications", *International Conference on Hydrogen Production (ICH2P), June 16-18, Istanbul, Turkey*.
- Cetin, E., Yilanci, A., Oner, Y., Colak, M., Kasikci, I., and Ozturk, H. K., 2009, "Electrical analysis of a hybrid photovoltaic-hydrogen/fuel cell energy system in Denizli, Turkey", *Energy&Buildings*, 41 (9), 975–981.
- Cetin, E., Keserlioglu, M. S. and Sazak, B. S., 2001, "Implementing of photovoltaic panel placement control by using Z80 Microcontroller", *6th Turkish-German Energy Symposium, 21-24 June 2001, Izmir-Turkey* (In Turkish).
- Colorado, 2010, <http://ecee.colorado.edu/~ecen2060/matlab.html>.
- Contrel Elettronica *RI-R48N Product Manual*, PDF version, 2009.
- Kasikci, I., 2008, *Electrical Power Systems Handbook*, first ed., Birsen Press, Istanbul.
- Kyocera™ 125GHT-2 Data Sheet PDF Version, 2009, <http://www.kyocera.com>.
- Nehrir, M. H., Wang, C. and Shaw, S. R., 2006, "Fuel cells: promising devices for distributed generation-understanding their modelling and need for control", *IEEE Power Engineering Magazine*, 4 (1), 47-53.
- Nexa™ Power Module User's Manual, Ballard Power Systems, 2003.
- Oner, Y., Cetin, E., Yilanci, A. and Ozturk, H. K., 2009, "Design and performance evaluation of a photovoltaic sun-tracking system driven by a three-freedom-spherical motor," *International Journal of Exergy*, Vol. 6, No. 6, pp. 853-867.
- Siemens Product Catalog, PDF version, 2009.
- Wang, C and Nehrir, M. H, 2009, *Instructions for running the 500-W PEM fuel cell stack dynamic models developed at the department of electrical&computer engineering*, Montana State University.
- Wang, C., Nehrir, M. H., and Shaw, S. R., 2005, "Dynamic models and model validation for PEM fuel cells using electrical circuits", *IEEE Transactions on Energy Conversion*, 20 (2), 442-451.

MATHEMATICAL MODELING AND SIMULATION OF HYBRID PARABOLIC SYSTEM IN KIZILDERE DENİZLİ TURKEY

Gökhan Uçkan^{*1}, Harun Kemal Öztürk^{*2}, Sıddık İçli^{*3}

¹ Computer Engineering Department, Pamukkale University, Denizli-Turkey

² Mechanical Engineering Department, Pamukkale University, Denizli-Turkey

³ Ege University Solar Energy Institute, İzmir-Turkey

ABSTRACT

Most countries are providing their needs of energy from coal, petrol, earth-gas or such fossil based energy sources. Using these fossil based resources, will cause environmental pollution and global warming. These resources will finish after sometime, because of their limited reserve left. After the petrol crises in 1971 some countries did not wanted to be dependent on petrol. Therefore they started to find alternative energy sources like renewable energy. They mostly focused on solar energy because they are more economically than other renewable energy sources, is easy to find and have no emission. With the technological improvements day by day, researchers worked on producing electrical energy by using solar energy. With time, electrical production through heated vapour took place. High temperatures are needed for electric production using steam and steam turbines. For high and medium temperature applications concentrating solar systems have to been used. One of the most used concentrating solar system, is the parabolic concentrating solar collector. The incoming solar beam is concentrated using parabolic concentrating collectors by reflecting the incoming beam from the reflecting surface to the absorber pipe which is replaced at the focus origin of the parabolic collector. In this work a mathematical modelling and simulation program of a hybrid geothermal power plant is supposed to built in Denizli Kizildere/Turkey. Assuming that the system would be supported with parabolic concentrating collectors. How to use fuzzy logic to find the optimum point where the heated water which comes from the parabolic concentrating collector will be oriented to the most suitable heat exchanger is explained. And also the developing of a simulation program using C# for controlling the system is described and the flowchart diagram is given.

Keywords: Parabolic Concentrating Collectors, Geothermal Plant, Heat Exchanger, Visual C#.Net

1. INTRODUCTION

As known many studies and researches have been done in the field of hybrid energy systems. But as a result their implementation cost have mostly become very high. Before realizing these kind of systems, they should be simulated by computer programs before for neglecting unwanted outcomes and surprises. In this study the energy gain from a hybrid energy system which is will take place in Kizildere/Denizli is supposed to be estimated by running computer programs; which will be developed according to the mathematical model of the system. The hybrid energy system which is accepted to take place in Kizildere/Denizli would be designed by two main parts. These will be the parabolic collectors part and the geothermal power plant part. All the system will work with the combination of these both systems as a hybrid system. The incoming sun light will be estimated using estimation methods developed by (Hotel 1976) [1]. Giving the time in hour and day using the day number inside the year; the direct sun beam can be estimated using a C# program. The energy outcome of the parabolic collectors according to the

* G.Uçkan: Tel: +90 506 566 4867; e-mail: guckan@pau.edu.tr
H.Öztürk: Tel: +90 533 2670649; e-mail: hkozturk@pau.edu.tr
S.İçli: Tel: +90-232-3435009; e-mail: siddik.icli@ege.edu.tr

parabolic collector types used in the system might be estimated as well. All these will be done using computer programs developed using Visual C#.Net.

2. ESTIMATION OF THE COMING SUN BEAM

The estimation of the sun beam can be done using Hottel's method which was developed in 1976. Due to this the incoming sunlight can be estimated using the equation 1 given below;

$$G_{cnb} = G_{on} \tau_b \quad (1)$$

where G_{cnb} is representing the clear sky normal beam radiation. G_{on} is the solar constant and will be taken as 1367 kw/m^2 . Where τ_b will be calculated using equation 2;

$$\tau_b = a_0 + a_1 \exp(-k / \cos \theta_z) \quad (2) \quad a_1 \text{ and } a_2 \text{ can be calculated from equations (3-5);}$$

$$a_0 = 0.4237 - 0.00821 (6 - A)^2 \quad (3)$$

$$a_1 = 0.5055 + 0.00595 (6.5 - A)^2 \quad (4)$$

$$k = 0.2711 + 0.01858 (2.5 - A)^2 \quad (5)$$

A is the altitude of the observer in kilometres, a_0 and a_1 are given for a standard atmosphere with 5 km visibility. For calculating τ_b the zenith angle θ_z has to be known or calculated from its necessary equations. These formulas can easily be calculated using C# codes.

3. DESCRIBING THE PARABOLIC COLLECTOR PART

As known parabolic concentrating collectors are mostly used in areas like industrial processes where high temperatures are needed [3]. As known parabolic collectors converting solar energy to thermal energy. The thermal energy gain of these parabolic concentrating collectors can be calculated from the equation 6 given below. According to the incoming sun beam the energy outcome of the parabolic concentrating collector can be estimated using this equation. Figure.1 shows the typical construction of a parabolic concentrating collector.

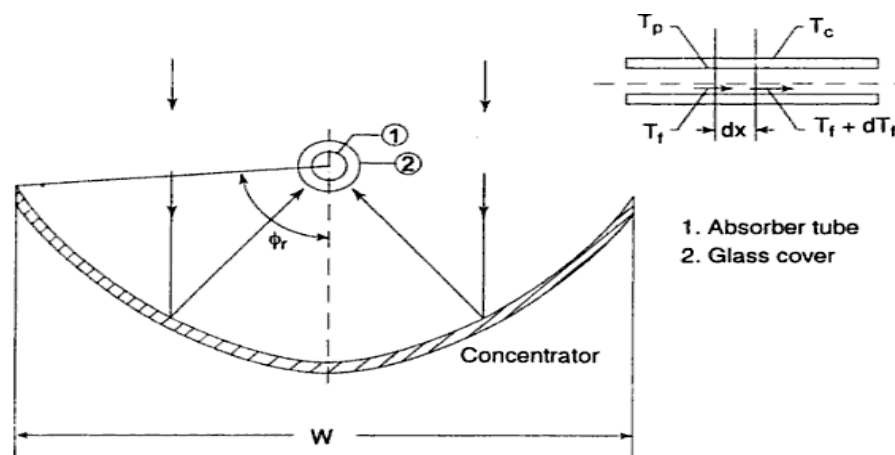


Figure 1. Typical construction of a parabolic concentrating collector.

dq_u = useful heat gain rate for a length dx ,

ρ = specular reflectivity of the concentrator surface,

γ = intercept factor, the fraction of the specularly-reflected radiation intercepted by the

absorber tube,
 $(\tau\alpha)_b$ = average value of the transmissivity-absorptivity product for beam radiation,
 U_l = overall loss coefficient,
 T_p = local temperature of absorber tube, and
 T_a = ambient temperature.
 θ_r = rim angle.

The useful energy gain for a unit area can be easily calculated from the equation 6. given below [2];

$$dq_u = [I_b r_b (W - D_0) \rho \gamma (\tau\alpha)_b + I_b r_b D_0 (\tau\alpha)_b - U_l \pi D_0 (T_p - T_a)] dx \quad (6)$$

The useful energy gain dq_u for dx can be calculated using a software program written in C#. Taking the integral of both sides of this equation according to the surface area of the parabolic concentrating collector module; the overall energy gain of one module will be calculated. Using the Romberg or Simpson method in the C# program this integral can be solved. A sample code of taking the integral using the Simpson method is given below [2].

```
double SimpsonIntegration(Function y, double a, double b, int n)
{
    int i;
    double h, sum1 = 0, sum2 = 0, totalsum;
    /* define h as the length of each sub-integration */
    h = (b - a) / (2 * n);
    for (i = 1; i <= n - 1; i++)
    {
        sum1 += y(a + (2 * i * h));
        sum2 += y(a + (2 * i * h) + h);
    }
    totalsum = ((y(a) + 4 * y(a + h)) + 2 * sum1 + 4 * sum2 + y(b)) * h / 3;
    return totalsum;
} // end of SimpsonIntegration
```

Here the “totalsum” will give the result of this integration, a and b are the ranges for the parabolic concentrating collector area. By multiplying this result with the number of modules used in the system, we will get the useful energy gain for all the parabolic concentrating collectors used in the system.

4. CALCULATING THE ENERGY GAIN ACCORDING TO THE PARABOLIC MODULES WE DECIDED TO USE IN THE GEOTHERMAL SYSTEM

By knowing the technical details like the geometry and performance characteristics of each parabolic concentrating collector module; It will become much more easier to calculate the energy gain of the parabolic collector system. When we have enough technical information about our parabolic solar collectors [4], which are planning to use in the system. It will be simple to calculate the energy gain for each module. By just entering the system efficiency, surface area and the estimated coming (direct) sun beam into the program using a form written in C# we will get the result on the screen. The technical details of parabolic concentrating collector module we suppose to use in the system is given in Table 1 below.

Table 1. Geometric and Performance Features of the Parabolic Collector Modules supposed to be used in the Geothermal System

Geometry	
Total Solar Collector Length	115m 377ft
Net Aperture Area	667m ² 7,180ft ²
Total Mirror Area	750m ² 8,073ft ²
Number of Modules	8 per Solar Collector Assembly
Module Aperture Length	13.9m 45.6ft
Module Aperture Area	83.4m ² 898ft ²
Rim Angle	82.5 Degrees
Geometric Concentration	75:1
Absorber Tube Diameter	80mm 3.15 In
Glass Envelope Diameter	125mm 4.92In
Receiver Length	4.72m 15.5ft
Performance	
System Efficiency	68%
Thermal Output	455kw-th
Annual Energy Generation	1.000MWh-th

By using the formulations the energy gain from one parabolic module will be calculated from the equation 7.

$$E = S \cdot A \cdot M \quad (7)$$

E= Energy Gain of the parabolic system.

A= Surface area of each Parabolic Collector Module.

M=Number of Modules used.

S= System Efficiency of each Parabolic Collector Module.

The form developed using visual studio.net is given in Figure 2.

Figure 2. Shows the form where the parameters have to be enter into the textbox before running the program for calculation.

The program codes are given below;

```
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Text;
using System.Windows.Forms;

namespace WindowsApplication1
{
    public partial class Form1 : Form
    {
        public Form1()
        {
            InitializeComponent();
        }

        private void button1_Click(object sender, EventArgs e)
        {
            double e, s, a, m;
            s = Convert.ToDouble(textbox1.text);
            a = Convert.ToDouble(textbox1.text);
            m = Convert.ToDouble(textbox1.text);
            e = s * a * m;
            label4.text = e;
        }
    }
}
```

5. MODEL OF THE GEOTHERMAL POWER PLANT USED IN KIZILDERE DENIZLI

The geothermal power plant used in Kızıldere/Denizli is shown in Figure.3

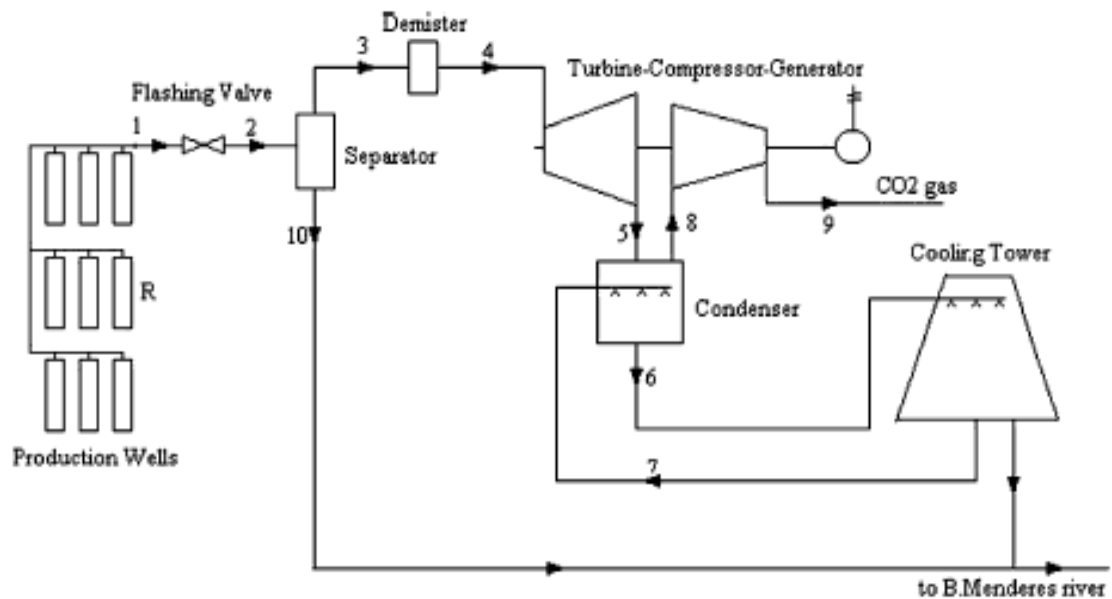


Figure 3. The Geothermal Power Plant used in Kızıldere Denizli.

The thermal energy coming from the parabolic collectors, will be directed to the heat exchanger placed at different parts of the geothermal plant. To the most suitable heat exchanger which will increase the heat of the fluid inside the geothermal plant shown in Figure 4. This will be selected using the result of a fuzzy software program. The selection of the heat exchanger will be done according to the degree of the fluid coming from the parabolic concentrating collector. This will be done by comparing the degree of the fluid with the cutting factor calculated by a mat-lab program according to the function members described by an expert of the system. For example if the degree of the fluid is below 120 degrees, which is nearly the temperature of the fluid coming from the production wells of the geothermal plant; Then the software program will decide to open the valve A which is a colder place according to valve C which will operate heat exchanger No1. Figure 4 shows the replacement of the heat exchangers at the geothermal system. The computer software will operate to redirect the coming heated fluid from the parabolic collector to the most suitable heat exchange positioned in the geothermal power plant to increase the overall heat of the fluid inside the geothermal plant. Then it will be given to the Turbine to produce electricity.

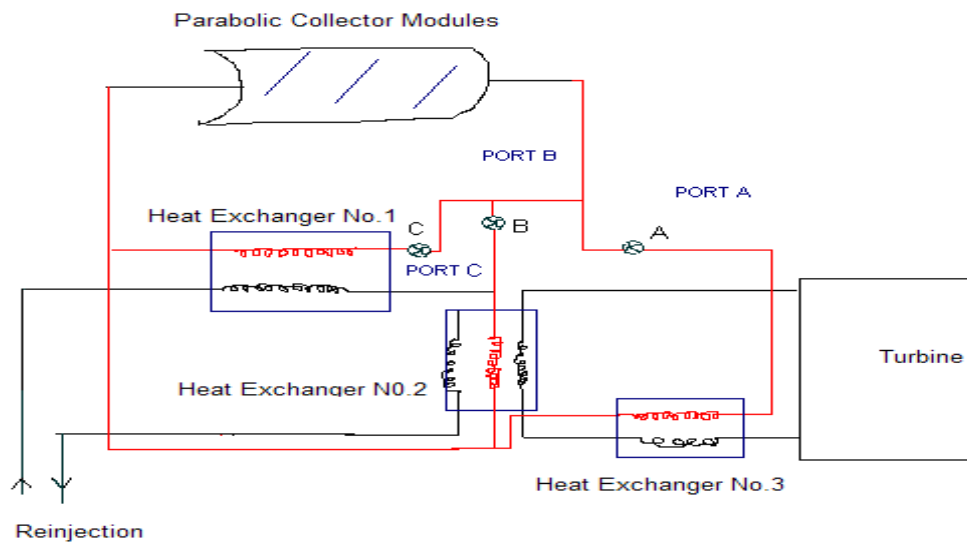


Figure 4. Heat exchangers replaced in the geothermal plant.

In Figure 5 the flowchart of a standard software program for controlling the system is shown.

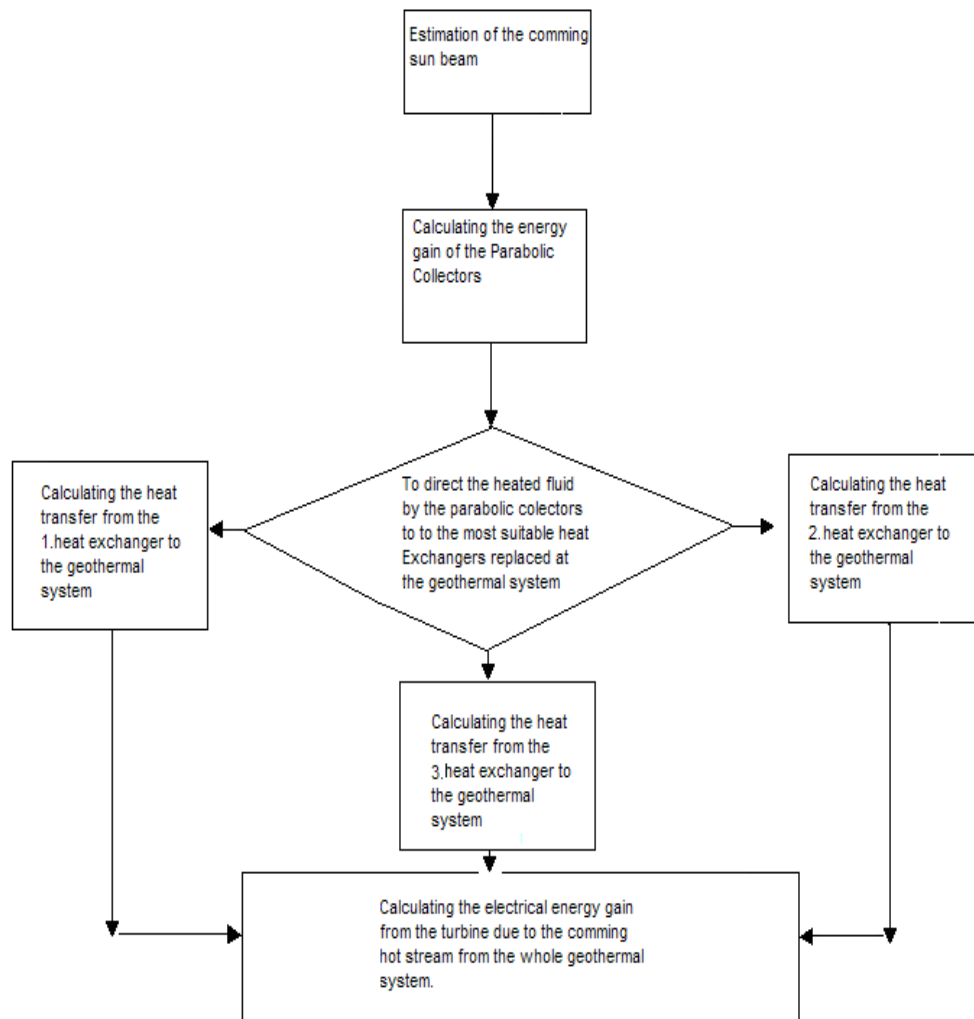


Figure 5. Flowchart, shows the steps that a software program should follow to control all the system.

6. CONCLUSION

As know building such energy systems are much high in expenses and are difficult to rebuild after their construction is finished. Therefore these kind of systems should be tested before realizing them using simulation programs. This work gives an overview about a hybrid energy system, their control and how simulation programs can be developed. The algorithm to build a simulation program for a hybrid energy system which is supposed to be realized in Kızıldere/Denizli Turkey is explained. This work also gives a general description about how such a hybrid energy system will work. The way of developing simulation and control programs for such kind of systems using C#.Net is briefly shown.

REFERENCES

- Available online 20 February 2010. *Solar Engineering of Thermal Processes*, Second Edition Jhon A.Duffie, William A.Beckman; A Willey-Interscience Publication [1]
- http://www.codeproject.com/KB/cs/Iteration_Methods.aspx [2]
- "Solar thermal collectors and applications", *Progress in Energy and Combustion Science* 30 (2004) pp.231-295, Soteris A. Kalogirou [3]
- Performance Of A Parabolic Trough Solar Collector*; Master of Science in Engineering at the University of Stellenbosch, By Michael John Brooks; February 2005. [4]

DETAILED ENERGY CONSUMPTION ASSESSMENT OF DIFFERENT SUPERMARKET REFRIGERATION CONFIGURATIONS IN LUXEMBOURG

A. Bertrand, D. Koster*

Public Research Centre Henri Tudor, Resource Centre for Environmental Technologies (CRTE), Luxembourg

ABSTRACT

This paper provides information on the energy consumption structure of four supermarket refrigeration systems of different configurations in Luxembourg. The distribution of the energy consumption between 7 components (cabinets, compressors, fans, pumps, etc.) in relation to the total energy consumption is presented and discussed here. This data will allow energy auditors who have access to the total electricity consumption of a supermarket, to estimate the distribution of the energy consumption to individual components. Furthermore, the full load hours of the main components are calculated here as a support for energy consumption estimations of similar systems.

Keywords: energy consumption, components, refrigeration system, measurement campaign, full load hours

1. INTRODUCTION

Electricity prices for industry in the EU-27 increased by 42% over the period of 2005 to 2009 [Eurostat, 2010]. As such, more and more companies consider Life Cycle Costs (LCC), which estimates, amongst others, the costs occurring by the use of a process, as a criterion for their decision-taking procedures when considering buying new equipment. For the optimisation of existing equipment, the companies are conducting energy audits, which define and assess improvement measures to reduce their energy consumption. In both cases of assessing new and existing equipment, energy consumption must be estimated, as measured data are (generally) not available.

The problem with energy consumption estimations is that they are often not accurate. For example, an internal project comparing the energy consumption estimations (heat and electricity) of 3 sites with their real, measured, energy consumption, showed that the estimated values were varying between – 173% and + 58%, the best match being an overestimation of 9% of the heat consumption of one of the sites. These large deviations are not necessarily due to poor work, but because it is difficult to estimate the energy consumption of variable load systems. In the past, energy consumption estimations were performed considering either a constant functioning (in term of power and time) of the component, or a staged functioning for a specific period of time. Nowadays, systems are not operating on a constant basis, so their power use varies considerably over time. This variability is making it difficult to estimate the average functioning time, and therefore the energy consumption, of technical components.

The objective of this paper is to improve the quality of energy audits of supermarkets by providing information on the energy consumption structure of four different refrigeration systems. This data was obtained during a measurement campaign of one year in the framework of the ANIA-project (ANalyses et gestion des impacts environnementaux et de la consommation énergétique d'Installations frigorifiques dans le secteur Agro-alimentaire) [Bertrand, Koster, 2008]. More specifically, the distribution of the energy consumption

* Corresponding author; E-mail: alexandre.bertrand@tudor.lu; Tel: +352 42 59 91 – 607

between 7 components (cabinets, compressors, fans, pumps) in relation to the total supermarket electricity consumption is presented and discussed here. This data will allow energy auditors who have access to the total electricity consumption of a supermarket, to estimate the distribution of the energy consumption to individual components. When available, values from similar studies are included to support the presented data. Furthermore, the full load hours of the main components are calculated here as a support for energy consumption estimations of similar systems.

2. SYSTEM DESCRIPTION

The four refrigeration systems assessed are installed in supermarkets in the towns of Ettelbrück, Brill, Bettembourg and Echternach (Luxembourg). The positive cooling systems (around -10°C evaporation temperature) of the first two supermarkets are equipped with direct evaporation systems (except for the air-conditioning – ac – unit of the supermarket in Brill, which is indirect), while the last two have an indirect (using propylene glycol) evaporation system for their positive cooling. The negative cooling (around -38°C evaporation temperature) system in Ettelbrück is autonomous, sharing the same (indirect) dry cooler as the positive cooling system. The negative cooling systems of the other 3 supermarkets consist of two-stage systems, which means that their condensation is not achieved via the dry cooler of the system, but via a heat exchanger coupled to the cold side of the positive cooling system. For all supermarkets, the condensation of positive cooling is achieved indirectly via dry coolers. The refrigeration systems in Brill and Echternach have both two indirect condensation circuits, so that two pump groups are used on these sites. The refrigeration is used for cabinets and cold rooms, as well as for air-conditioning, in the case of Brill and Echternach. An overview of the major parameters of the four systems is given in Table1.

Table 1. Refrigeration systems description

Parameter	Ettelbrück	Brill	Bettembourg	Echternach
Positive cooling power [kW]	67	183	68	169
Positive electrical power [kW]	25	83	30	72
Evaporation temperature [°C]	-10	-13,5	-14	-12
Positive evaporation system [-]	Direct	direct	indirect	indirect
Positive cooling refrigerant [-]	R134a	R134a	R134a	R134a
Electrical power of the indirect evaporation pumps [kW]	-	2,0/2,0 (ac)	2,2	3,0/4,0
Negative cooling power [kW]	22	28	16	29
Negative electrical power [kW]	16	10	5	10

Table 2. Refrigeration systems description (continued)

Parameter	Ettelbrück	Brill	Bettembourg	Echternach
Evaporation temperature [°C]	-38	-37	-38	-37
Negative evaporation system [-]	Stand-alone	2-stage	2-stage	2-stage
Negative cooling refrigerant [-]	R404A	R744 (CO ₂)	R744 (CO ₂)	R744 (CO ₂)
Electrical power of the dry cooler pumps [kW]	4,0	7,5	2,2	7,5
Electrical power of dry cooler fans [kW]	16,00	3,20	1,10	6,00

The positive cooling compressors of Ettelbrück and Bettembourg, as well as one compressor from Brill, are controlled via a bypass of the pistons. The other compressors are controlled via an on/off control. The evaporation temperature of the positive cooling systems in Bettembourg and Echternach is raised by 3,4K during the nights, and 2,1K on days that the supermarkets were closed. The condensation temperature was relatively constant for Ettelbrück, while the temperatures of the other sites were slightly adapted

according to the external temperature, as is illustrated in Figure 1 (the data gap for the site in Ettelbrück is due to data acquisition problems).

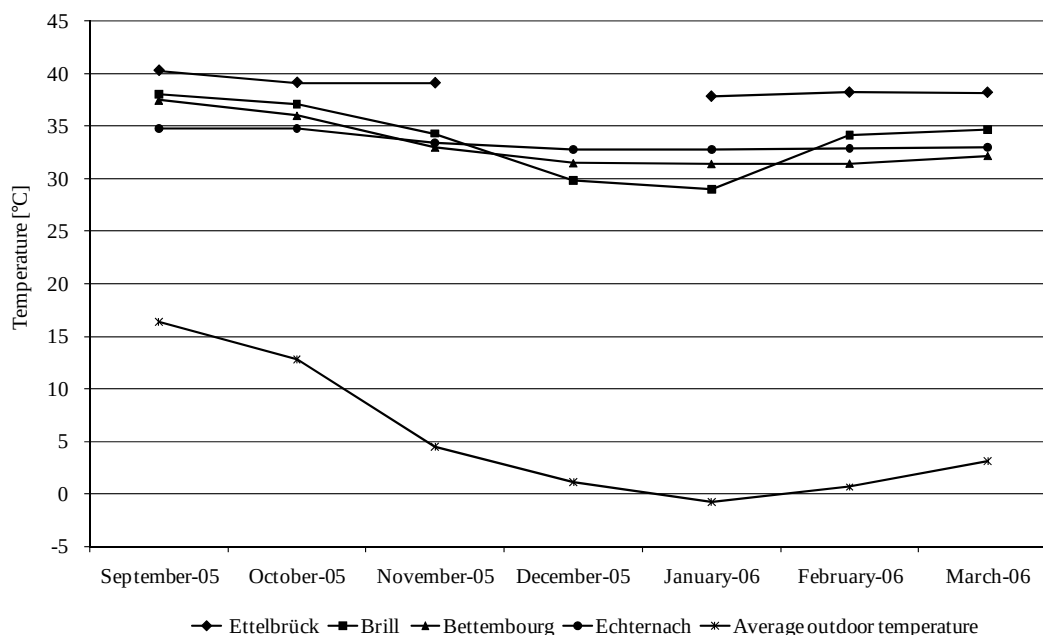


Figure 1. Average condensation temperatures and outdoor temperature

The pumps of the indirect evaporation and condensation circuits use an on/off control and are therefore running at a constant power level. The fans of the dry coolers switch on or off one at the time, as a function of the circuit temperature. Except for the site in Ettelbrück, heat recovery is used for hot water and air preheating. The positive indirect cooling systems are equipped with liquid suction heat exchangers. These heat exchangers are mostly used to protect the compressors against liquid inflows, as well as to obtain a subcooling of about 20 K to raise the thermal power (and thus improve the Coefficient Of Power – COP – of the system). For further details on the systems, see [Bertrand, Koster, 2008].

3. ENERGY CONSUMPTION AND CO₂-EMISSIONS OF THE CONSIDERED SYSTEMS

3.1 MEASUREMENT CAMPAIGN

The measurement campaign started the 1st of April, 2005 and finished the 31st of March, 2006. Energy consumption data of the dry coolers, the compressor unit (positive and negative cooling), the pumps (evaporation and condensation side) and of the different cooled items (cabinets and frozen rooms), as well as of the total refrigeration energy consumption was gathered using MDVH3106 / DVH3113 counters. For the period between April and August 2005, the values of the energy counters were collected on a monthly basis. Due to an adaptation of the measurement equipment, the data acquired during the period from September 2005 to March 2006 was downloaded from a central digital data acquisition system.

The average outdoor air temperature and relative humidity over the period considered are represented in the figure below.

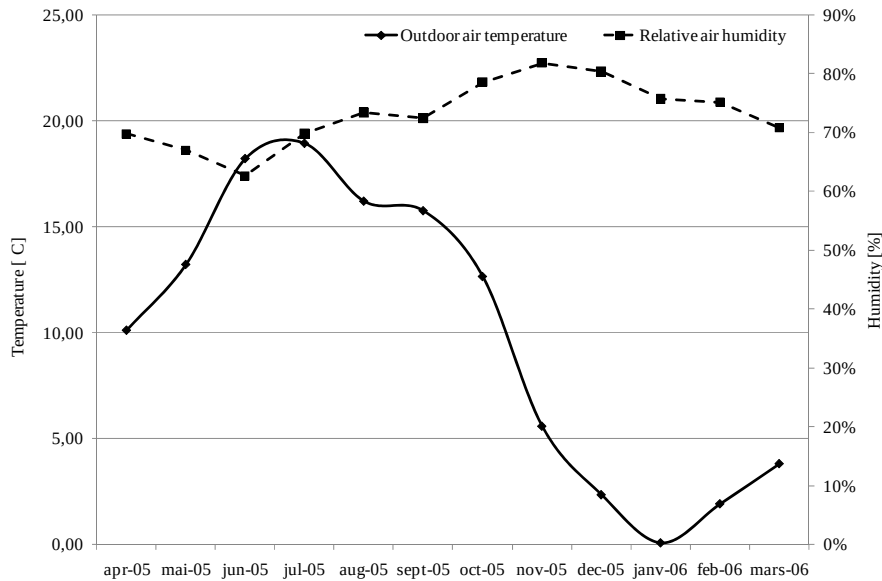


Figure 2. Monthly average outdoor air temperatures and relative air humidity [Massen, 2006]

3.2 ENERGY CONSUMPTION DISTRIBUTION

The different relative energy consumptions are given in Table 3. The percentages are related to the total supermarket electricity consumption.

Table 3. Relative energy consumption distribution

	<i>Ettelbrück</i>	<i>Brill</i>	<i>Bettembourg</i>	<i>Echternach</i>
Total supermarket electricity consumption [kWh/a]	703 570	809 804	354 870	1 381 536
Total measured refrigeration energy consumption [kWh/a]	431 309	694 654	227 328	833 950
Relative measured refrigeration energy consumption [%]	61%	86%	64%	60%
Sum of the refrigeration components energy consumption [kWh/a]	422 142	599 255	212 922	815 106
Dry cooler fans [%]	4,5%	0,4%	0,4%	0,7%
Negative cooling compressor unit [%]	16,0%	5,2%	5,3%	4,4%
Positive cooling compressor unit[%]	15,2%	39,6%	26,5%	26,4%
Sum of positive and negative compressor units [%]	31,2%	44,7%	31,9%	30,8%
Negative cooling items[%]	13,7%	15,2%	11,3%	10,2%
Positive cooling items [%]	6,3%	4,4%	8,3%	10,5%
Sum of positive and negative cooling items [%]	20,0%	19,6%	19,6%	20,7%
Condensation pumps [%]	4,3%	6,7%	4,2%	3,3%
Evaporation pumps [%]	-	2,6%	3,9%	3,5%

The energy consumption of the refrigeration systems represented more than 60% of the total electricity consumption of the supermarket. In Brill, this value even reached 86%, which is due to the partial use of the cooling equipment for air conditioning and the use of an ice machine. This higher contribution to the total electricity consumption is probably also due to the fact that the supermarket was newly build and used several energy-saving

measures (e.g. concerning lightning). A value of 47% is mentioned for medium and low outdoor air temperatures in relation to supermarkets in Sweden by Baxter,(2003), 56% for a supermarket in France (measurement campaign over 6 months) [Enertech, 2001], 44% for a direct evaporation supermarket and 58% for an indirect evaporation supermarket in California (values based on average daily energy from October 2002 to June 2003) [Faramarzi R., Walker D., 2004].

3.2.1 Dry cooler fans

The energy consumption of the dry cooler fans in the supermarkets in Brill, Bettembourg and Echternach is almost negligible. The reason for this very small energy consumption is that the heat exchange surfaces are very important for these sites, and as the heat transferred is proportional to the surface as well as the mass flow, the latter can be reduced, thus diminishing the energy use of the fans. The energy consumption of the fans in Ettelbrück, on the other hand, is about 4,5% of the total supermarket electricity. From Table 4, it is clear that in Ettelbrück, the specific heat exchange is 2 to 3 times smaller than those of the other supermarkets, which is due to limited available space. For this reason, the specific power is about 23 times more important. The absence of heat recovery as well as the indoor installation and the necessity for noise abatement measures are further reasons for the increased energy consumption.

Table 4. Data on the heat exchange surface and specific power of the dry coolers

<i>Parameter</i>	<i>Ettelbrück</i>	<i>Brill</i>	<i>Bettembourg</i>	<i>Echternach</i>
Thermal power [kW _{th}]	70	300	96	224
Specific power [W _{el} /kW _{th}]	229	11	12	27
Heat exchange surface [m ²]	309	4 028	1 427	2 138
Specific heat exchange surface [m ² /kW _{th}]	4,41	13,43	14,86	9,54

The contributions of the energy consumption of the condenser of a direct, respectively indirect evaporation system in California in relation to the total energy consumption of the supermarkets were 3% and 4% [Faramarzi R., Walker D., 2004].

The full load hours of the fans of the considered systems are as follow:

Table 5. Full load hours of dry cooler fans

	<i>Ettelbrück</i>	<i>Brill</i>	<i>Bettembourg</i>	<i>Echternach</i>
Dry cooler fans [hrs]	1964	893	1320	1593

If these values are to be used for an estimation of the energy consumption of a supermarket refrigeration system, it is advised to choose the appropriate value according to the above-mentioned description of the dry cooler system. The most relevant aspects to consider for the choice of the value are presence of heat recovery and heat exchanger surface.

3.2.2 Compressors

The energy consumption of the compressors (total of positive and negative cooling compressors) represents about 31% of the total supermarket electricity consumption. In the case of Brill, the compressors consumed as much as 45% of the total energy used, which is probably linked to the additional functionality due to the air-conditioning support. A measurement campaign of 2 supermarkets in California showed that, when related to the daily energy consumption, the compressors represented 30% for the direct evaporation system and 33% for the indirect configuration [Faramarzi R., Walker D., 2004].

The energy consumption of the positive cooling compressors of Bettembourg and Echternach represented about 27% of the total electricity consumption, while the compressors of Brill reached 40%. The negative cooling compressors of these sites

contributed only to 5% to the energy use of the supermarket. For the stand-alone system in Ettelbrück, the positive cooling compressors used 15% and the negative cooling compressors 16% of the total energy. This difference between stand-alone and 2-stage configuration is due to the fact that the work needed to compress the refrigerant from a temperature level of -10°C to the condensation temperature is taken over by the positive cooling system for the 2-stage configuration (thereby reducing the energy consumption of the negative cooling compressors). This compression work is produced by the negative cooling compressors of the stand-alone system, therefore reducing the energy consumption of the positive cooling compressors.

With regards to the potential efficiency losses of indirect cooling systems due to lower evaporation temperature (linked to the difference of temperature necessary for the heat exchanger, see for example [Clodic et al., 1998]), it is interesting to note that this effect was avoided by the use of the internal liquid-suction heat exchanger. This heat exchanger allows the superheating of the exiting refrigerant, leading to an increased heat exchange surface (as the superheating is not done in the normal heat exchanger anymore) and thus enabling a higher evaporation temperature. Without this heat exchanger, according to the manufacturer, the evaporation temperature would be about 3K lower, which would lead to a reduction in efficiency at full load of approximately 6%-7,5% [Renz, 2003]. Further information on the energy efficiencies of the compressors can be found in Bertrand and Koster (2008).

The full load hours of the compressors are given below:

Table 6. Full load hours of compressors

	<i>Ettelbrück</i>	<i>Brill</i>	<i>Bettembourg</i>	<i>Echternach</i>
Negative cooling compressor unit [hrs]	7047	4179	3794	6100
Positive cooling compressor unit [hrs]	4274	3859	3138	5064

The choice of the full load hours for energy consumption estimations should be based on the configuration of the positive and negative cooling systems (e.g. values from Ettelbrück for stand-alone configuration). The higher full load hours of the site in Echternach implies that the compressor units are not, compared to the other supermarkets, over-sized. For the production of the necessary cooling, the compressors have therefore to work longer and at high power levels. So, for compressor units working often close to their maximum power level, it might be relevant to use full load hours similar to those obtained in Echternach.

3.2.3 Cooling items

In this project, 20% of the electricity consumption of the supermarket is related to the electricity use of cabinets and cold storage rooms. The positive cooling cabinets represent between 5% to 11%, the negative cabinets between 10% and 15% of the total electricity consumption. This electricity consumption is due to the use of lighting, fans, electrical defrost heating (direct evaporation circuits), anti-fog heating of the windows, handrails and doors heating and condensate heating (to avoid freezing in the condensate pipe). In [Faramarzi R., Walker D., 2004], these cases represented 12% (direct evaporation) and 18% (indirect evaporation) of the energy consumption.

The energy consumption of the electrical defrost associated with the direct evaporation system of the cabinets of Ettelbrück and Brill were measured separately, and represented 0,5%, respectively 0,7% of the total energy use of the supermarket. Based on confidential information provided by the manufacturer, the specific energy consumption of the electrical defrost system is calculated as attaining 165 kWh/m²*a, the surface of reference being the total surface of exhibition of a cabinet. The indirect evaporation systems were defrosted by stopping the brine circulation and using the supermarket hotter air, thus avoiding the necessary energy consumption.

The measurement campaign did not provide further information on the distribution of the energy use in accordance of the other components. A review of energy consumption distributions for different types of cabinets can be found in [Monier V. et al., 2007].

Because of the large number of types and manufacturers, the energy consumption estimation and distribution analysis of the cabinets and storage room is particularly difficult. In certain cases, the cabinet manufacturer have information on the Direct electrical Energy Consumption (DEC) of their equipment, which can be found on the homepage of the Eurovent association www.eurovent-certification.com. Typical DEC values for different kinds of cabinets are given in [Monier V. et al., 2007].

3.2.4 Pumps

The energy consumption of the constant-flow pumps of the indirect *evaporation* units were 4%, while the *condensation* systems represented between 3% and 7% of the total electricity consumption. The value of 3% measured for the air-conditioning of the supermarket in Brill should not be considered, as the system was new and not fully operational at the beginning of the measurement campaign. The pumps represented 3% of the energy consumption of the considered supermarket in [Faramarzi R., Walker D., 2004].

The full load hours of the pumps are given in Table 7.

Table 7. Full load hours of pumps

	<i>Ettelbrück</i>	<i>Brill</i>	<i>Bettembourg</i>	<i>Echternach</i>
Condensation pumps [hrs]	7619	7254	6806	6100
Evaporation pumps [hrs]	-	5217	6247	6966

As mentioned above, the pumps are controlled in an on/off mode. As such, the only time when they are not working is when the refrigeration system is not used. Interestingly, the assertion often stated in the framework of energy consumption estimation, that full load hours of the dry coolers and of the condensation pumps should be identical, is not confirmed here. In the case of the evaporation pumps, we would propose to use, as a first approximation, about 6600 hours for pumps similar to those used here. For condensation pumps, the proposed approach for the dry cooler fans would also be of application here.

3.2.5 Additional equipment consumptions

As can be seen in **Table** , the sum of the measured energy consumption of the different components and the total measured energy consumption for the refrigeration system differs by 2% in Ettelbrück and Echternach, 7% in Bettembourg and 16% in Brill. This supplementary energy consumption is due to additional equipment, like the centralised control system, the fans of the electricity cabinets and of the equipment rooms. In Bettembourg, the higher energy consumption, compared to Ettelbrück and Echternach, is most probably due to the use of a compressed air system for the control of pneumatic valves. In Brill, the high additional energy consumption is due to an ice machine necessary for the fish display cabinets. Considering this aspect, future energy consumption measurement campaign should try to assess separately the energy use of such a unit, as it is, in this case, consuming more energy than the fans of the dry cooler or the pumps.

Based on the data presented here, we would propose to consider an additional 2% in energy consumption which takes into account the basic components mentioned above: the centralised control system and several small fans.

4. DISCUSSION AND CONCLUSIONS

The contribution of the energy consumption of different components of the refrigeration systems in four supermarkets in relation to the total electricity consumption

are presented in this paper. Results from similar studies are mentioned and show that the values obtained are of a corresponding magnitude. As such, energy auditors assessing refrigeration system of similar configuration and use, have, in this paper, an overview of the importance of the different components and their contribution to the energy consumption of a supermarket. Using the data provided, energy optimisation measures can be better prioritised.

Based on the measured energy consumption, the full load hour values of different components analysed in this paper are given here. The variations in values between the four considered sites show that the definition of only *one*, commonly applicable, full load hour is not feasible. This is due to differences in user behaviour, system configuration and component behaviour and control. Therefore, the values mentioned in this paper should be used as a guide only, when considering the energy consumption estimation of similar systems, in terms of technology and use.

ACKNOWLEDGEMENTS

The project was co-financed by the supermarket group Cactus S.A., the Environmental Agency and the Ministry of Higher Education and Research of Luxembourg. This paper is co-financed by the European FP6-project SEMS – Sustainable Energy Management Systems, contract number 038514 and the Ministry of Higher Education and Research of Luxembourg.

REFERENCES

- Baxter V. (compiler), *IEA annex 26: advanced supermarket refrigeration / heat recovery systems – final report volume 1 – executive summary*, http://www.ornl.gov/sci/engineering_science_technology/Annex26/Annex-26-final-report.pdf, Oak Ridge National Laboratory, 2003
- Bertrand A., Koster D., ANIA - *Analyses et gestion des impacts environnementaux et de la consommation énergétique d'installations frigorifiques dans le secteur agro-alimentaire – rapport final*, [http://www.crte.lu/cms/crte/content.nsf/0/CB023779A8F6499AC12575600052FB40/\\$file/Ania_Rapport_final_-_1.0.pdf](http://www.crte.lu/cms/crte/content.nsf/0/CB023779A8F6499AC12575600052FB40/$file/Ania_Rapport_final_-_1.0.pdf), Resource Centre for Environmental Technologies, 2008
- Clodic D., Le Pellec C., Darbord I., *Efficacité énergétique de systèmes direct et indirect en froid commercial – étude comparative*, Journée Française du Froid, Association Française du Froid, 1998
- Enertech, *Diagnostic électrique d'un supermarché de moyenne surface – rapport final*, <http://sidler.club.fr/RSuperm.PDF>, Enertech, 2001
- Eurostat, *Electricity prices for industrial consumers* (ten00114), http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables#, Eurostat database, 2010
- Faramarzi R., Walker D., *Investigation of secondary loop supermarket refrigeration systems*, http://www.energy.ca.gov/reports/2004-04-23_500-04-013.PDF, California Energy Commission, 2004
- Massen F, *Meteorological data of the Lycée Classique in Diekirch*, <http://meteo.lcd.lu/>, Lycée Classique Diekirch, 2006
- Monier V., Mudgal S., Iyama S., Tinetti B., *Preparatory studies for eco-design requirements of EuPs – Lot 12 : commercial refrigerators and freezer* (final report), http://www.ecofreezercom.org/docs/BIO_EuP_Lot_12_Final_Report.pdf, BIO intelligence service, 2007
- Renz H., *Anwendung von alternativen Kältemitteln aus Sicht eines Verdichterherstellers – Besonderheiten, Anforderungen*, www.bitzer.de/_doc/download.php?d=a&f=av-0301-de.pdf, Bitzer Kühlmaschinenbau GmbH, 2003

SPECIAL PAINT APPLICATIONS FOR ENERGE SAVING AND CO₂ EMISSION REDUNTION IN WINTER

*Mitsuyuki Kawakami*¹ and Kimihiro Yamanaka**

Graduate School of System Design, Tokyo Metropolitan University

ABSTRACT

The purpose of the present study is to quantitatively verify the energy-saving effects in a realistic context by experimentally applying our originally developed paint to actual buildings. For different heat sources, namely, sunlight (radiant heat) in summer and heating appliances (convective heat) in winter, separate approaches are required for verification; the experiments and discussions in the present study are for winter. The obtained results are summarized as follows: 1) In winter, the mechanism of the energy-saving effect is the infrared emission from the coating, which controls the rise of the surface temperature of the inner wall and reduces the temperature difference between inside and outside. 2) T he use of the special paint in winter provides energy savings and carbon dioxide emission reductions of about 20%.

Keywords: Energy saving, CO₂ reduction, Radiation, Ceramic, Jade natural ore

1. BACKGROUND

In recent years, global warming has become a pressing problem that must be addressed not only in Japan but throughout the world (Ministry of the Environment Government, 2008.; T. Ishihara, 2010.). In the field of architecture, heat reflective insulating paint is spreading as a new technology for reducing the cooling and heating load for air conditioning, and thereby achieving energy savings. Although the merits of such paints are being confirmed at the field level, conventional calculation formulas cannot be applied because the mechanisms of the energy-saving effects are different from those of conventional insulation materials; thus, there remains a problem of verification (S. Kakizaki, 2004.).

Against this background, there are various kinds of conventional studies (M. Kawakami, 2008.; M. Kawakami, 2009.). the purpose of the present study is to quantitatively verify the energy-saving effects in a realistic context by experimentally applying our originally developed paint to actual buildings. For different heat sources, namely, sunlight (radiant heat) in summer and heating appliances (convective heat) in winter, separate approaches are required for verification; the experiments and discussions in the present study are for winter.

2. PAINT CHARACTERISTICS AND DETAILS OF EXPERIMENT

The specialized paint used in this research was ceramic insulation paint, which is paint blended with ceramic beads to confer increased solar reflectance (Table 1).

Figure 1 shows a photograph of the buildings used in the experiment. The outside walls, inside walls and ceiling of each building were coated with either ceramic insulation paint (building A) or ordinary paint (building B). Both buildings had the same volume, plot orientation and specifications. The internal space of each building was a Japanese-style

* kawakami@tmit.ac.jp

* kiyamana@cc.tmit.ac.jp

room with *tatami* flooring (28.155 m²). To verify the energy-saving effect of the ceramic insulation paint in winter, we compared the rise in air temperature in buildings A and B when heating was provided using an air conditioner system. We also compared changes in the rise of air temperature and wall temperature, as well as the air conditioner power consumption.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Changes in rise of air temperature and inside wall surface temperature

The changes in air temperature and inside wall surface temperature in buildings A and B throughout the experimental period are shown in Figure 2. In the table, temperature (vertical axis) is plotted against measurement time (horizontal axis). As can be seen from the table, the air temperature rose more quickly in building A on every day of the measurement period when the heating was on. It is also apparent that the profiles for the change in air temperature and inside wall temperature in building B are virtually identical, whereas in building A the air temperature increased with greater efficiency than the inside wall temperature.

Table 1. Solar reflectance of coating

Paint	Solar reflectance (%)		
	Overall wavelength region 300–2100 nm	Visible region 300–780 nm	Infrared region 780–2100 nm
Ceramic insulation paint	60.3	37.6	86.2
Highly reflective paint A	55.6	32.9	81.6
Highly reflective paint B	53.7	33.5	76.8

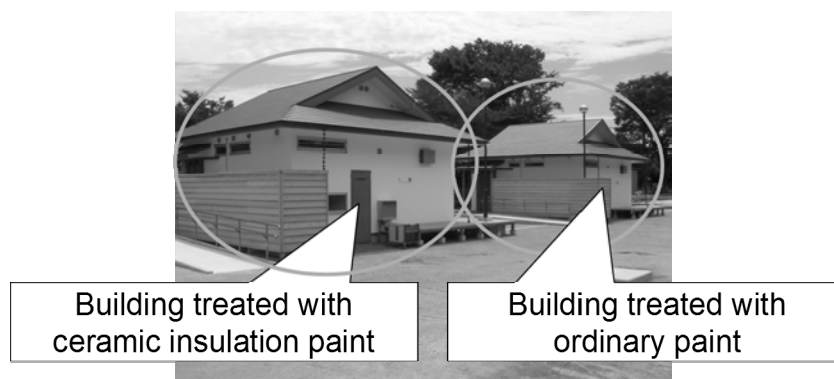


Figure 1. Photograph of buildings

Figure 3 shows changes in the difference between air temperature and inside wall temperature in buildings A and B. The mean difference between air temperature and inside wall temperature was 2.52 °C in building A, but only 0.20 °C in building B, a difference of 2.32 °C. The largest difference between air temperature and inside wall temperature in buildings A and B during the measurement period was 2.6 °C, on December 18. Using these data values as a profile, a test of the difference between mean values found that the difference between air temperature and inside wall temperature was significantly greater in building A than building B ($p < 0.01$), indicating that where surfaces are coated with ceramic insulation paint, the air temperature rises more efficiently than the inside wall temperature while the heating is on.

3.2 Changes in air conditioner power consumption

The changes in power consumed by the air conditioners in buildings A and B throughout the measurement period are shown in Fig. 4. Power consumption (left vertical

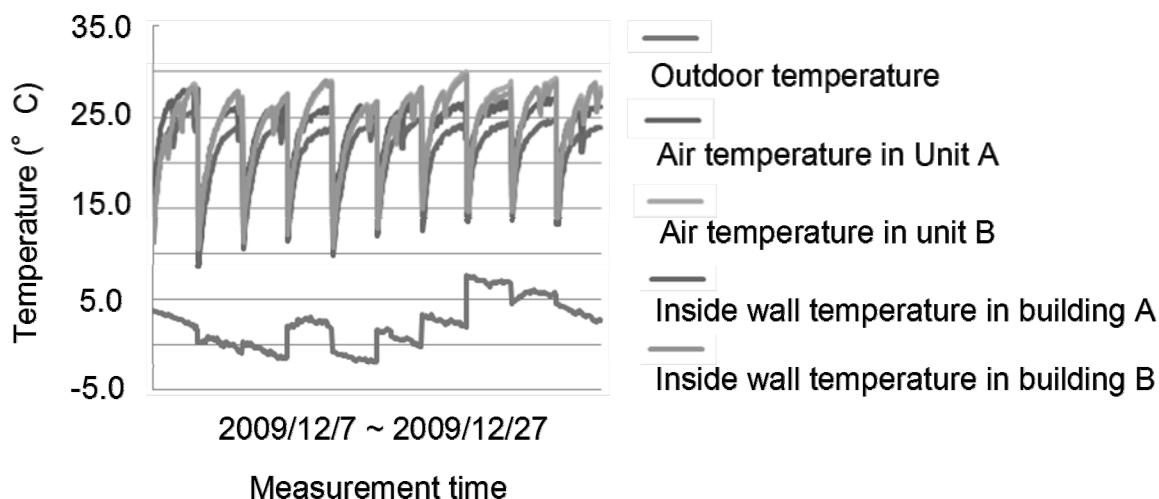


Figure 2. Change in room air temperature and internal wall surface temperature

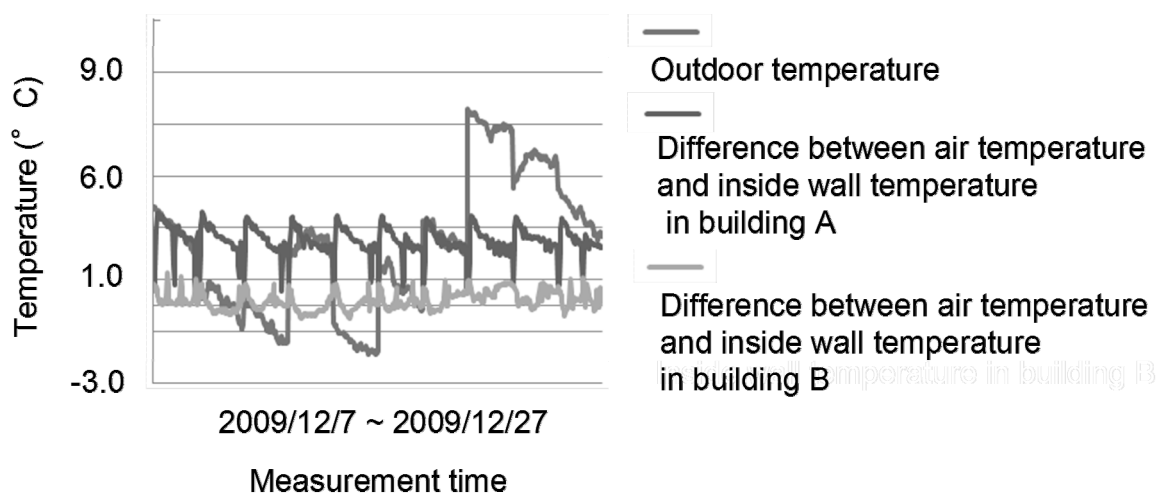


Figure 3. Change in difference between room air temperature and internal wall surface temperature

axis) is plotted against measurement time (horizontal axis) and temperature (right vertical axis). As can be seen in the graph, air conditioner power consumption in building A tended to be lower than that in building B.

During the measurement period, mean daily air conditioner power consumption for heating was 1418.42 W in building A and 1810.18 W in building B, a difference of 391.76 W (21.6% reduction). The largest difference between air conditioner power consumption in buildings A and B during the measurement period was 613.1 W, on December 20. Using these data values as a profile, a test of the difference between mean values found that air conditioner power consumption was significantly lower in building A than building B ($p < 0.01$), indicating that where surfaces are coated with ceramic insulation paint, the power consumption required for heating is reduced.

3.3 Heat flux verification experiment using steel boxes

Three cubic boxes with sides of 500 mm were used in this experiment, and were

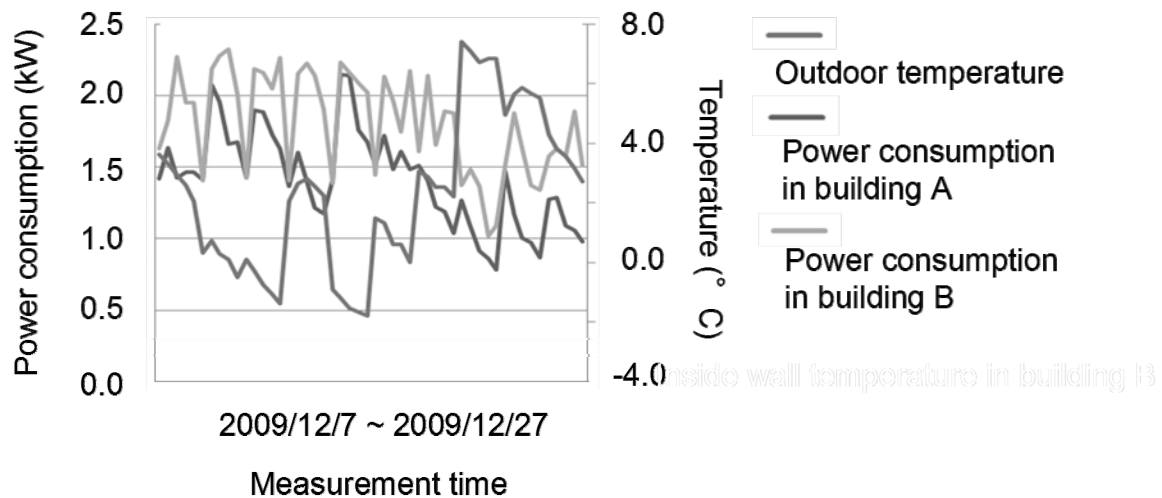


Figure 4. Change in air conditioning power consumption

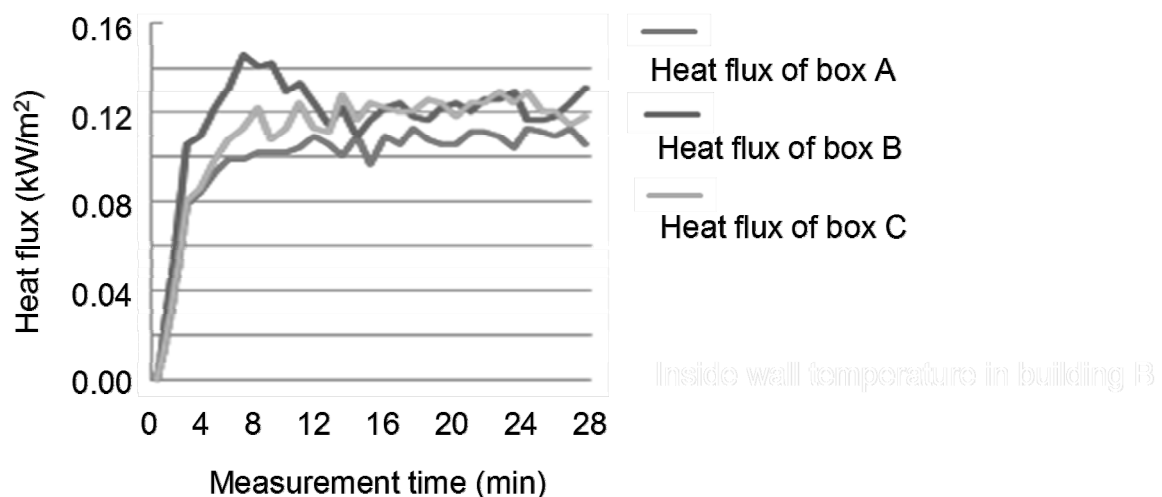


Figure 5. Change in heat flux

painted with ceramic insulation paint (box A), ordinary paint (box B) or highly reflective paint (box C). In the experiment, the amount of heat flowing out of each box was measured when heat was generated in the box by a small heater.

Changes in heat flux are shown in Figure 5. The heat flux of each box (vertical axis) is plotted against time (horizontal axis). It is clear from the graph that heat flux was lower in box A than boxes B and C. This shows that coating surfaces with ceramic insulation paint has the added effect of decreasing the heat flux.

4. MECHANISM OF EFFECT

Compared to ordinary paints, this ceramic insulation paint is characterized by an extremely high infrared emissivity of 94.6%, and produces a coating film with a large surface area. At equal temperatures, the amount of infrared radiation is determined by

emissivity and surface area, increasing as these two properties increase. It is therefore thought that when thermal energy is absorbed by the coating of ceramic insulation paint, it is immediately re-emitted as infrared waves. If this hypothesis is correct, we would expect the rise in inside wall temperature in building A to be suppressed to a greater extent than building B. The measured values in our experiment measuring the energy-saving effect in winter confirmed that this is the case. Because heat transfer varies in proportion to the temperature gradient, suppressing the rise in inside wall temperature in winter when the heating is running means that the temperature gradient between the building's internal surfaces and exterior (outside air) is minimized. The application of ceramic insulation paint thus keeps down the inside wall temperature and minimizes the temperature gradient between inside and outside, thereby inhibiting the outflow of heat.

5. ENERGY-SAVING EFFECT

The results of this experiment demonstrate the effect of ceramic insulation paint in cutting carbon dioxide emissions in winter. The conditions of air conditioner operation followed the Japan Refrigeration and Air Conditioning Industry Association's 'Criteria for Calculating Air Conditioner Power Consumption' in terms of annual standard operating days (169 heating days, Oct 28 - April 14) and operating times (18 h, 6:00 to 18:00)

When we ran a simulation on the experimental building taking the measured value of the roof surface temperature as the sol-air temperature and substituting this into the formula for insulation in conventional buildings, the energy-saving effect in winter was a reduction of 1101.8 kWh in power consumption and a reduction of 606.0 kg in carbon dioxide emissions (19.8% reduction).

6. CONCLUSION

The obtained results of this study are summarized as follows.

(1) In winter, the mechanism of the energy-saving effect is the infrared emission from the coating, which controls the rise of the surface temperature of the inner wall and reduces the temperature difference between inside and outside.

(2) The use of the special paint in winter provides energy savings and carbon dioxide emission reductions of about 20%.

REFERENCES

- Ministry of the Environment Government [Online]., *Global Environment Global Environment News Headline.*, *The FY 2008 Annual Report on Ozone Layer Monitoring* (2009). Available: <http://www.env.go.jp/en/headline/headline.php>.
- Mitsuyuki Kawakami & Kimihiro Yamanaka, "A Study on Enagy-efficient Temperature Control", *Proc. of ICEST 2009: International Conference on Environmental Science and Technology*, in CD-ROM, (2009).
- Mitsuyuki Kawakami & Kimihiro Yamanaka, "Enagy-efficient Temperature Control for Aging Workers, Extending the Work Life", *TUT Press*, pp.25-32, (2009).
- Seizo Kakizaki, "Idea of architectural insulation", pp.132-154, *Ohmsha*, (2004).
- Thoru Ishuhara, "Toward Low Energy Technology Oriented Nation, Japan", *Information Processing Society*, vol.51, No.7, p.890, (2010)

GREEN ROOFS FOR URBAN AREAS: EFFECT OF IRRIGATED-SOIL COVERED ROOFS FOR COOLING

Kazuhito Ishimatsu^{*1,2}, Matthew Leach², Keitaro Ito¹, Yasunori Mitani³

¹ Department of Civil Engineering, Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka, 804-8550, Japan

² Centre for Environmental Strategy, University of Surrey, Guildford, Surrey GU2 7XH, UK

³ Department of Electrical Engineering and Electronics, Kyushu Institute of Technology, 1-1. Sensui-cho, Tobata-ku, Kitakyushu-shi, Fukuoka, 804-8550, Japan

ABSTRACT

In the past decades, the number of green roofs for improving the indoor thermal environment during midsummer has been increasing year on year in Japan. It has, however, been reported that plants hardly have a role to contribute to reduce inside temperature. This is because almost all of the amelioration of the environment is caused by evaporation directly from the soil-covered roof. Although several tests for substantiating the phenomenon has been implemented so far, comparative experiment of such strategy for converting the theory into residential environment at human scale has never progressed. The present study aims to monitor how indoor thermal environment is affected by irrigated soil-covered roof by means of real residential models, and via an outside configuration of buildings in a Japanese urban area to explore the achievement of thermal comfort by encompassing natural methods and engineering technology. Firstly, as the preparatory experiment, the effect that plants on roofs have on cooling inside a building was assessed. We set up five miniature green roofs, 500*500[mm]. Each of the five roofs was under experimental conditions as follows; A1 [irrigated light soil and Plantain (*Plantago asiatica* L.)], A2 [irrigated light soil and Sedum (*Sedum mexicaum* Britt.)], A3 [irrigated light soil and Lawn (*Zoysia tenuifolia* Willd.)], A4 [irrigated light soil], A5 [bare]. Inside temperatures of styrofoam boxes, 150*250*150[mm], under each roof were monitored. Secondly, as the main experiment, contributions of an irrigated light soil of depth 50[mm], sunlight reflection and green wall by loofah (*Luffa cylindrica*) for cooling inside a building were assessed by means of six Green Cubes, 2500*2500*2500[mm]. Each of the six cubes was under experimental conditions as follows; Cube 1 [roof: irrigated light soil; wall: green walls], Cube 2 [roof: untreated; wall: green walls], Cube 3 [roof: sunlight reflection; wall: untreated], Cube 4 [roof: sunlight reflection; wall: green walls], Cube 5 [roof: untreated; wall: untreated], Cube 6 [roof: irrigated light soil; wall: untreated]. Inside temperatures and electricity consumption for running an air-conditioner in each of the six cubes were monitored. As a result, to cover roofs with irrigated soil may be the most beneficial way because of lower cost for installing and maintenance than any green roofs, with only slightly lower performance. Next, it was shown that green wall was in first place, followed by irrigated light soil and sunlight reflection, in order of effective approach for achieving a desirable indoor thermal environment, in terms of metrics for both inside temperature and electricity consumption for running the air-conditioner. Besides, in case of combining treated roof and walls, the effect of cooling potential was naturally higher. Thus, it can be seen that irrigated soil-covered roof plays a role to cooling inside temperature and reducing consumption of the air-conditioner. Although the environmental functions of green roofs are often highlighted (e.g., mitigation of rainwater runoff, reducing heat islands effect and so on), the cost-effectiveness is not superior due to the fact that installation and maintenance costs are so expensive. There are a number of inexpensive alternative ways to achieve similar environmental aims. It should be noted that green roof gets to be essential only in the case of rehabilitating urban biodiversity under the condition that open space in urban area is usually small.

* Corresponding author; E-mail: k.ishimatsu@surrey.ac.uk; Tel: +44 1483 689559

Keywords: Green roof; Green wall; Electricity consumption; Urban biodiversity; Irrigated- soil covered roof; Heat-island phenomenon

1. INTRODUCTION

Urban green spaces can be important elements contributing to urban sustainability [Esbah et al. 2009], because they can contribute to the reduction of various types of pollution, the improvement of microclimatic conditions, the absorption of stormwaters, and the prevention of flooding [Georgi and Dimitriou 2010]. In terms of the improvement of the microclimate in urban spaces, deciduous trees offer shade during summer and as Georgi and Dimitriou [2010] note, the suitable selection of the right species can enhance cooling through evapotranspiration, reducing the temperature by up to 3.1°C. Evapotranspiration creates pockets of lower temperature in an urban environment, known as the “phenomenon of oasis” [Georgi and Dimitriou 2010]. Conversely, it permits the sun to shine through the branches during the winter [Georgi and Dimitriou 2010].

Nowadays, increased urbanisation has had and continues to have a negative impact on urban green spaces [Kong and Nakagoshi 2006], and affects the urban microclimate [Georgi and Dimitriou 2010] as represented by “heat-island phenomenon”. The phenomenon is caused when the heat from the sun is absorbed into buildings by the roof and then released back into the air resulting in urbanised city centres one or two degrees hotter than suburbs and rural areas [Wilkinson and Reed 2009], consequently requiring further electricity consumption for running air-conditioners. A large proportion of this energy is used to maintain internal building temperatures through heating and cooling systems [Castleton 2010]. The spectrum of environmental impact produced by the use of energy resources in urban areas ranges from effects at a local level, such as the heat-island phenomenon and air and water pollution, to regional and global effects, such as the global climatic change [Ferrante and Mihalakakou 2001].

Although it has been suggested to restore and conserve urban green spaces, there are rarely enough open spaces due to urban densification. This is why the green roof, which has benefits for air and water filtering, thermal buffering, storage and protective properties [Schrader and Böning 2006], has become one of the rapidly developing urban ecological engineering fields in Japan. A green roof is comprised of the following components: a roof structure; a waterproof membrane or vapour control layer, an insulation, a root barrier to protect the membrane, a drainage system, a filter cloth, a growing medium (soil) consisting of inorganic matter, organic material (straw, peat, wood, grass, sawdust) and air, and plants [Wilkinson and Reed 2009]. Green roofs are generally classified into two types of systems: extensive and intensive [Molineux et al. 2009]. Intensive systems are more like roof gardens supporting large trees and shrubs, but requiring deep substrates and regular maintenance [Molineux et al. 2009]. Extensive systems are generally substrate-based with a vegetated layer or a sedum mat, either on its own with a sponge membrane for moisture retention or with a substrate base; offering between 2.5 and 10 cm deep root zones due to restrictions by weight loading on a building's structure [Molineux et al. 2009]. In extensive roof greening concepts, sedum species and other species of the sedo-scleranthetea plant community have been the most commonly used plants [Castleton 2010; Schrader and Böning 2006], because they require minimum maintenance and are easy to install as part of a roof system [Castleton 2010].

According to Japanese Ministry of Land, Infrastructure, Transport and Tourism [2009], the total green roof area in Japan has been increasing steadily during the past decade (Fig. 1). Almost all of these green roofs aim to improve thermal environment of midsummer [Iijima 2008], and about half of these roofs are extensive roofs with lawn grass or sedum [Japanese Ministry of Land, Infrastructure and Tourism 2009]. However, regarding sedum it can be killed by Japanese hot and humid summer, and disturb Japanese biodiversity because it is not a Japanese native plant. As well, it has been reported that evapotranspiration velocity from soil area without any plants is similar to one from lawn grass or sedum areas, therefore in terms of mitigating heat-island phenomenon

irrigated-soil may be key, regardless of plants [Ferrante and Mihalakakou 2001; Ohno et al. 2006].

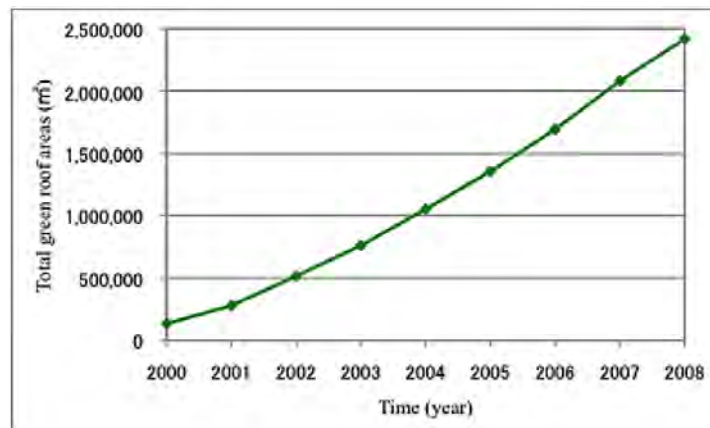


Fig.1. Process of total green roof areas in Japan (Japanese Ministry of Land, Infrastructure and Tourism, 2009)

Furthermore, regarding not only sedum but also all plants, the process of evapotranspiration takes place in the plants' leaves rather than in the soil, drawing energy from the environment and not directly from the soil-covered building [Pearlmutter and Rosenfeld 2008]. In contrast, the despite watered-soil layer on a roof can indeed be used as an effective means of evaporative cooling and has the particular benefit of producing this cooling during the hottest hours of the day [Al-Turki et al. 1995; Pearlmutter and Rosenfeld 2008]. Furthermore, plants in green roofs prevent watered-soil from evaporating for cooling. In terms of cooling purposes, the role of plants on roofs is for shading [Ferrante and Mihalakakou 2001; Palomo and Barrio 1998]. Therefore, it has been suggested that cover-materials other than plants could provide the wetted soil surface with substantial shading, without limiting the potential for cooling by evaporation, that is to say, the possible ways of reducing this energetic liability is to "eliminate" the exposed roof by shading the roof area with some structures like tight weave mesh or in some way sheltering it with a substantially thick layer of soil [Pearlmutter and Rosenfeld 2008]. The reductions in energy usage and external surface temperatures of roofs can also lead to a reduction in the heat-island phenomenon of the city centres [Wilkinson and Reed 2009].

Although several tests for substantiating the effect of evaporative roof for cooling has been implemented so far [Al-Turki and Zaki 1991; Al-Turki et al. 1995; Pearlmutter and Rosenfeld 2008], comparative experiment of alternative strategies for converting the theory into residential environment of human scale has never progressed. The present study aims to monitor how indoor thermal environment is affected by irrigated-soil covered roof by means of real residential models, and via an outside configuration of building in the Japanese urban area to explore the achievement of thermal comfort by encompassing natural methods and engineering technology.

2. METHODS

2.1 Preparatory experiment

The preparatory experiment aimed to monitor the effect that plants on roofs have on cooling inside buildings and research possibilities for Japanese native plants for green roofs, which has taken place at the rooftop of civil engineering building at Tobata Campus of Kyushu Institute of Technology, Japan, from 24th August 2007 to 2nd September 2007.

2.1.1 Plants for covering roof

We selected Plantain (*Plantago asiatica* L.) as a Japanese native plant for green

roofs, because the plant can endure severe condition on roof to be alive at cracks between asphalts or concretes, and efficiently cover soil with leaves due to perennial and rosette plant. In order to compare it with representative plants of existing Japanese extensive green roofs, Lawn (*Zoysia tenuifolia* Willd.) and Sedum (*Sedum mexicaum* Britt.) were adopted.

2.2.2 Experimental setup

Four cells were composed of the following components (sorted by lowest to highest): a Styrofoam box, 150*250*150[mm]; a drainage layer (FD DRAIN LN; produced by TAJIMA ROOFING LTD.), 500*500[mm]; a root barrier membrane (FD FILTER; produced by TAJIMA ROOFING LTD.), 500*500[mm]; and light soil (FD SOIL; produced by TAJIMA ROOFING LTD.), 50[mm]. In addition 5th cell was exposed without a set of miniature green roof. Temperature sensors (ECH2O PROBE; produced by DECAGON DEVICES, INC.) were set in each Styrofoam box, a meteorological sensor (VANTAGE PRO2; produced by DAVIS INSTRUMENT) was set close to the cells. Except the 5th cell, the others were given 700ml irrigation to soil twice a day, 5:30 and 17:30. Table 1 shows the conditions of miniature green roofs.

Table 1. Conditions of miniature green roofs

	A1	A2	A3	A4	A5
Roof covers	Irrigated soil 50 mm and Plantain	Irrigated soil 50 mm and Sedum	Irrigated soil 50 mm and Lawn	Irrigated soil 50 mm	Bare

2.2 Main experiment

The main experiment aimed to monitor how indoor thermal environment is affected by watered soil-covered roof by means of real residential models, which has taken place at the Eco-energy Trial Unit “Green Cube” at Tobata Campus of Kyushu Institute of Technology, Japan, from 11th August 2009 to 5th September 2009.

2.2.1 Green Cube

Each “Green Cube” (Fig. 2), 2500*2500*2500[mm], is composed of a concrete floor slab, steel frames, glass walls and roof slab, and a Styrofoam thermal insulator and thin steel plate on the roof slab with an air conditioner, electricity consumption meter (TIBT-R; produced by ENEGATE CO., LTD.) and a temperature censer (HYGROCHRON; produced by KN LABORATORIES, INC.). These cubes were totally sealed for the experimental term.



Fig.2. Eco-energy Trial Unit “Green Cube”

2.2.2 Plant for covering wall

We selected Loofah (*Luffa cylindrica* (L.) Roem.), because the plant can grow up

easily and blind the walls with large leaves. Each seedling was planted in each flowerpot, afterward, set along each wall which has a support net for helping Loofha to climb the wall.

2.2.3 Experimental setup

The effect of irrigated soil covered-roof for cooling inside temperature was monitored by means of combining irrigated soil covered-roof, sunlight reflection coating-roof and green wall. The irrigated soil covered roofs were composed of a drainage layer (FD DRAIN LN; produced by TAJIMA ROOFING LTD.), 2500*2500[mm]; a root barrier membrane (FD FILTER; produced by TAJIMA ROOFING LTD.), 2500*2500[mm]; and light soil (VIVASOIL; produced by TOHO-REO CO., LTD.), 50[mm]. The sunlight reflection coating-roofs were painted sunlight reflection coating (HAISTA-SHATARO; produced by HITACHI CHEMICAL INDUSTRIAL MATERIALS CO., LTD.) on the steel plates. A meteorological sensor (VANTAGE PRO2; produced by DAVIS INSTRUMENT) was set on the field of these experimental equipments. The irrigated soil covered-roofs were irrigated with 10000 ml once a day, 10:00. The flowerpots planted seedlings of Loofah were given 750 ml irrigation to the soil twice a day, 10:00 and 16:00. Table 2 shows the conditions of green cubes.

Table 2. Conditions of Green Cubes

	Cube 1	Cube 2	Cube 3	Cube 4	Cube 5	Cube 6
Roof	Irrigated soil	Utreated	Sunlight reflection	Sunlight reflection	Utreated	Irrigated soil
Walls	50 mm Loofah	Loofah	Utreated	Loofah	Utreated	50 mm Utreated

2.2.4 Electricity consumption

Power consumption data (Standard RS-485) measured by the electricity consumption meter was sent to IP network converter via a wireless terminal and onto the campus LAN. We monitored electricity consumption of each cube operating each air conditioner with 27°C setting from 10:00 to 18:00 for sunny days only during the experiment.

3. RESULTS AND DISCUSSION

3.1 Preparatory experiment

Fig. 3 shows the temporal profile for temperature of each cell on 24th August 2007, from 6:00 to 18:00. Unfortunately, other days during this experimental period were not sunny all the day. We, therefore, selected the date because continual sunshine was important for the experiment.

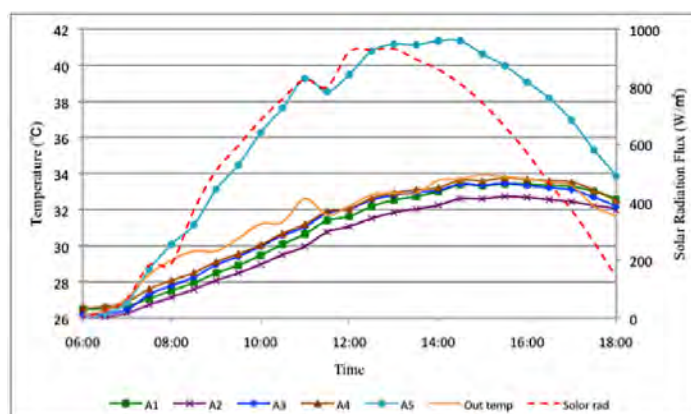


Fig. 3. Temporal profile for temperature of each cell on 24th August 2007

Firstly, it can be seen that while A5 temperature rapidly rose with increasing solar radiation flux, the others mildly rose like the outside temperature. That A5 temperature rose as high as over 41 degrees was due to the direct sunlight.

Secondly, observing A1, A2, A3 and A4, it is shown that the temperature in A2 is slightly lower than the others. The cause is thought that Sedum effectively protected the soil surface from direct sunlight and made insulations of air pockets like mulching material, because Sedum's three-dimensional volume was more massive than Plantain and Lawn. However, the effect of A2 advantage for cooling was only around 1 degree compared to A1, A3 and A4, therefore it can safely be said that in extensive green roofs the type of plants hardly affect the function for cooling.

It can be concluded that given the fact that Sedum can disturb Japanese urban biodiversity, to adopt Sedum for green roofs is not beneficial. In addition, in Japan the law for controlling invasive alien species has been in force since in June 2005 and updated year on year. On 1st February 2010, twelve types of alien plants have been restricted [Japanese Ministry of the Environment 2010]. Sedum has not been restricted yet, however, Japanese Ministry of the Environment has continued to collect more information on other alien species, and the number of restricted species has increased year on year. Thus green roofs covered by nonnative plants like Sedum may not be a sustainable way. In terms of cooling, to cover roofs with irrigated soil may be the most beneficial way because of lower cost for installing and maintenance than any green roofs, with only slightly lower performance. Furthermore, according to Palomo and Barrio [1998], to select light soil can reduce the thermal conductivity as well as weight, because a less dense soil has more air pockets and is hence a better insulator [Castleton 2010]. Finally, in case of needing plants for soil covered-roof, own native plants should be adopted as covering plant instead of nonnative plants.

3.2 Main experiment

3.2.1 Indoor temperature

Fig. 4 shows the average temperatures during five hours from 11:00 to 16:00 for six sunny days without air conditioners.

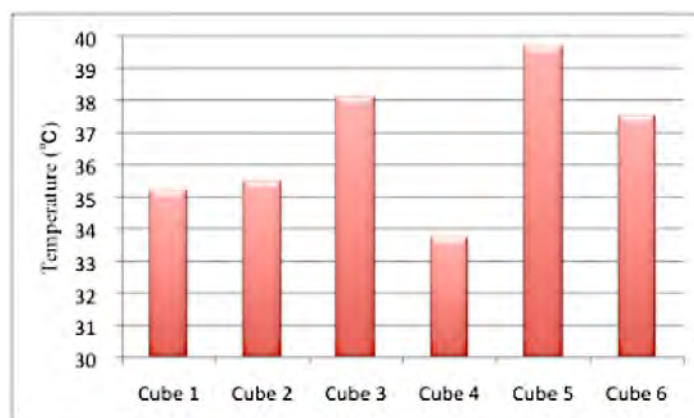


Fig. 4. Average indoor temperatures without air conditioners, from 11:00 to 16:00, for six sunny days

Table 3. Green coverage of green walls on 17th August

	Cube 1	Cube 2	Cube 4
Green coverage (%)	63.0	68.2	76.5

Firstly, comparing between Cube 3 and Cube 6, it can be seen that irrigated soil covered-roof is more effective than sunlight reflection roof regarding the cooling effect.

Furthermore, the former is also superior to the latter in terms of providing insects and plants habitats. However, the way to paint roofs for sunlight reflection is so easy, and roofs with steep slope can't be covered with soil. Thus, in general it is sensible to consider soil covering for flat or gently sloping roofs, with other roofs painted for sunlight reflection.

Secondly, comparing between Cube 1, Cube 2 and Cube 4, Cube 4 (with sunlight reflection roof and loofah walls) temperature was much lower than the others. It is, however, highly possible that Cube 4 is affected by the shade of a tree due to the fact that there is a big tree to the east of Cube 4. The tree covered Cube 4 with shade for the whole morning. In addition, green coverage of Cube 4 was the highest in the three cubes (Table 3). Therefore, it can be anticipated that it would have been similar to Cube 1 and Cube 2 if those cubes were under exactly same conditions. To sum up the result of Cube 1, Cube 2 and Cube 4, it is important for improving indoor thermal conditions to block building from direct sunlight. The greater the area of blocked direct sunlight, the greater the cooling effect.

3.2.2 Electricity consumption

Fig. 5 shows the average electricity consumption and temperature during five hours from 11:00 to 16:00 for eight sunny days, during which air conditioners were operational. Despite some influence from inherent variation in performance of individual air conditioner units, the results follow those of average temperature without sir conditioner (Fig. 4) closely.

Consequently, it was proven that irrigated soil covered-roof can reduce electricity consumption for cooling as well as sunlight days reflection painted-roof. According to Castleton [2010], the thicker the soil substrate on the roof, the better it reduces heat gain/loss into/out of the building. In addition, green walls can enhance the effect for cooling. It is argued that in case it is difficult to cover walls with plants, another ways to blind walls should be used instead of plants. Because the role of plants at walls in this experiment mainly was to protect from direct sunlight like a curtain.

The introduction of electro-mechanical air conditioning systems into the building, with their great energy expenditure, has become the standard alternative used to natural cooling [Palomo and Barrio 1998]. Meanwhile, a climatic conscious design of outdoor spaces and the appropriate use of natural components are key elements to reduce the outcome of unsound

evolution of urban areas where impermeable surfaces and denuded landscapes determine undesirable climatic effects and unhealthy life conditions [Ferrante and Mihalakakou 2001].

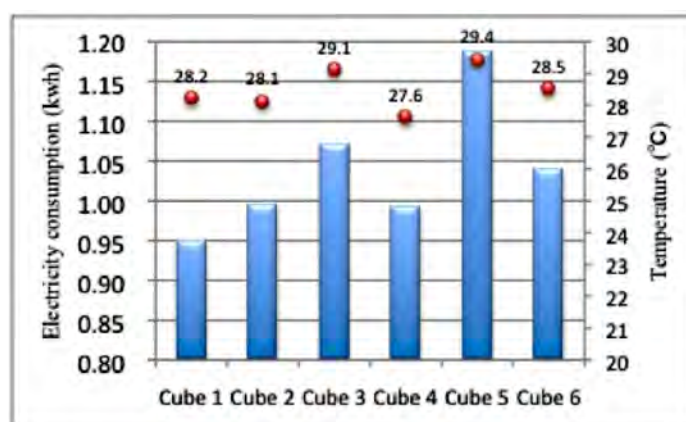


Fig. 5. Average electricity consumptions and indoor temperatures, from 11:00 to 16:00, for eight sunny days

4. CONCLUSIONS

At the start of the 21st century, rising energy costs coupled with increasing concerns about global warming related to CO₂ emissions, resulted in increasing interest in alternative, low and non-carbon based energy sources [Dovi et al. 2009]. Improving energy use efficiency is becoming increasingly important for combating rising energy costs and for fulfilling carbon emission reduction aims in the industrial sector [Dovi et al. 2009]. However, the ways to achieve this are never simple as they involve complicated ecosystem components. There are numerous problems, which modern society must face in seeking to secure a sustainable energy supply while also seeking to reduce the influence of energy use on climate changes and species diversity losses [Dovi et al. 2009]. The first step to avoid these problems is to increase the amount of open spaces and permeable surfaces as much as possible [Ferrante and Mihalakakou 2001].

Although the environmental functions of green roofs (e.g., mitigation of rainwater runoff, reducing heat islands effect and so on) are often promoted, the cost-effectiveness is not superior to alternatives due to the fact that installation and maintenance costs are so expensive. There are a number of inexpensive alternative ways to achieve similar environmental aims. It should be noted that green roof gets to be essential only in the case of rehabilitating urban biodiversity under the condition that open space in urban area is usually small.

For example, with the expansion of urbanisation world-wide, migrating songbirds increasingly encounter landscapes where fragmentation has resulted in small habitat patches embedded in an urban matrix [Matthews and Rodewald 2010]. Intensive green roofs can support animals and plants and play an important role in conserving urban biodiversity [Kim 2004]. It is nearly impossible to link fragmented habitats continuously on ground and build a habitat network [Kim 2004]. It is necessary to use green rooftops as "stepping stones" in building a network [Kim 2004]. Intensive green roofs contribute to the bio-diversity within the city and create habitats for birds and invertebrates [Wilkinson and Reed 2009].

On the other hand, Schrader and Böning [2006] reported that extensive green roofs also provides conditions for successive developments of soil biota (in this case, Collembola) and soil-forming processes which clearly contribute to urban biodiversity and compensate, at least in part, for conventional asphalt roofs. Despite their beneficial properties and ecological value for urban landscapes, green roofs should never be considered a justification for destroying natural or semi-natural habitats on the outskirts of cities and beyond [Schrader and Böning 2006]. Roof greening revalues cities but does not replace nature [Schrader and Böning 2006].

It can be concluded that green roofs should be focused on conserving and restoring urban biodiversity using own native plants. Most of the modern urban environmental issues represented by urban heat-island phenomenon can be resolved by replacing impermeable surfaces with permeable surfaces without huge cost.

REFERENCES

- Al-Turki AM, Zaki GM (1991) "Energy Energy saving through intermittent evaporative roof cooling". *Energy and Buildings*, 17:35-42.
- Al-Turki AM, Gari HN, Zaki GM (1995) "Comparative study on reduction of cooling loads by roof gravel cover". *Energy and Buildings*, 25:1-5.
- Castleton HF, Stovin V, Beck SBM, Davison JB (2010) "Green roofs; building energy savings and the potential for retrofit". *Energy and Buildings*, doi:10.1016/j.enbuild.2010.05.004.
- Dovi VG, Friedler F, Huisinigh D, Klemeš JJ (2009) "Cleaner energy for sustainable future". *Journal of Cleaner Production*, 17:889-895.
- Esbah H, Cook EA, Ewan J (2009) "Effects of increasing urbanization on the ecological integrity of open space preserves". *Environmental Management*, 43:846-862.
- Ferrante A, Mihalakakou G (2001) "The influence of water, green and selected passive techniques

- on the rehabilitation of historical industrial building in urban areas". *Solar Energy*, 70:245-253.
- Georgi JN, Dimitriou D (2010) "The contribution of urban green spaces to the improvement of environment in cities: Case study of Chania, Greece". *Building and Environment*, 45:1401-1414.
- Iijima K (2008) "Okujoryokukakukan no tayosei to donyushokubutsu". *The Japanese society of revegetation technology*, 34:338-343. (In Japanese)
- Kim KG (2004) "The application of the biosphere reserve concept to urban areas: the case of green rooftops for habitat network in Seoul". *Annals of the New York Academy of Sciences*, 1023:187-214.
- Kong F, Nakagoshi N (2006) "Spatial-temporal gradient analysis of urban green spaces in Jinan, China". *Landscape and Urban Planning*, 78:147-164.
- Matthews SN, Rodewald PG (2010) "Movement behaviour of a forest songbird in an urbanized landscape: the relative importance of patch-level effects and body condition during migratory stopover". *Landscape Ecology*, 25:955-965.
- Ministry of Land, Infrastructure, Transport and Tourism (2009) *Okujo/hekimen –ryokukakukan ha aratani donoteido sosyutsu saretanoka*. Available at: www.mlit.go.jp/common/000045480.pdf (Accessed 4 August 2010) (In Japanese)
- Ministry of the Environment (2010) *Gairai-seibutu-ho*. Available at: www.env.go.jp/nature/intro/index.html (Accessed 10 September 2010) (In Japanese)
- Molineux CJ, Fentiman CH, Gange AC (2009) "Characterising alternative recycled waste materials for use as green roof growing media in the U.K.". *Ecological Engineering*, 35:1507-1513.
- Ohno T, Yamamoto S, Maenaka H (2006) "Evapo-transpiration from Sedum Mat and Cynodon Turf". *The Japanese society of revegetation technology*, 69:431-436. (In Japanese and with English summary)
- Palomo E, Barrio D (1998) "Analysis of the green roofs cooling potential in buildings". *Energy and Buildings*, 27:179-193.
- Pearlmutter D, Rosenfeld S (2008) "Performance analysis of a simple roof cooling system with irrigated soil and two shading alternatives". *Energy and Buildings*, 40:855-864.
- Schrader S, Böning M (2006) "Soil formation on green roofs and its contribution to urban biodiversity with emphasis on Collembolans". *Pedobiologia*, 50:347-356.
- Wilkinson SJ, Reed R (2009) "Green roof retrofit potential in the central business district". *Property Management*, 27:284-301.

TWO-STAGE ANAEROBIC PROCESS FOR BIO-HYDROGEN AND BIO-METHANE COMBINED PRODUCTION FROM BIODEGRADABLE SOLID WASTES

Kvesitadze G., Sadunishvili T. , Dudauro T., Metreveli B., Jobava M.*

Durmishidze Institute of Biochemistry and Biotechnology, Tbilisi, Georgia

ABSTRACT

The overall goal of the work is the increase of energy output from biodegradable fraction of municipal solid waste (MSW). For these purposes development of cost-effective two-stage anaerobic fermentation process with bio-hydrogen and bio-methane combined production was introduced. Anaerobic hydrogen producing bacteria convert a large variety of carbohydrate sources (frequently obtained as refuse or waste products) mainly to hydrogen, CO₂ and volatile fatty acids. Since in natural environments hydrogen producing anaerobes coexist with methane forming ones which consume intermediate products of hydrogen fermentation including hydrogen and produce their own end products like methane and CO₂, the most obstacle to obtain hydrogen as the final product of hydrogen fermentation is associated with partition of hydrogen and methane fermentation processes in cost-effective way. Approach used for problem solution included the following: (i) search out low cost chemicals for partition of hydrogen and methane fermentations; (ii) isolation, study and reveal of high productive hydrogen producing bacteria; (iii) development of optimum conditions for bio-hydrogen and bio-methane sustainable production from biodegradable fraction of MSW. The use of 10% solution of sodium hydroxide provided practically full inhibition of methane forming bacteria. In thermophilic conditions and pH 9.0 cumulative bio-hydrogen productions made 82.5 l/kg dry organic matter. Percentage of hydrogen and carbon dioxide in the produced bio-hydrogen were – 50.1% and 49.8% correspondingly. Content of methane in bio-hydrogen didn't exceed 0, 1 %. Adding of inoculums of hydrogen producing bacteria promoted the increase of bio-hydrogen cumulative production up to 104 l/kg dry organic matter. Cumulative bio-methane production from the metabolite products of hydrogen fermentation made 520 l/kg dry organic matter. Methane and carbon dioxide percentage determined in obtained bio-methane was 78.6% and 21.4% correspondingly. Comparing energy data for two-stage anaerobic digestion with those for single-stage process resulting solely in bio-methane production shows that energy output from biodegradable fraction of MSW increases by 23 - 26% under two-stage anaerobic process. Bio-hydrogen and bio-methane combined production can be implemented at large scale biogas plants improving process economy. Introduction of such technology at the existing biogas plants needs low investments.

Keywords: bio-hydrogen, bio-methane, solid waste

1. INTRODUCTION

Anaerobic digestion of high humidity biodegradable solid wastes and wastewater resulting in methane containing biogas (bio-methane) and organic-mineral fertilizers production is considered as one of the effective processes for wastes minimization and environment protection in general. At large scale systems bio-methane is used for combined heat & power production. Nowadays, due to the commercialization of low cost and "CO₂ neutral" hydrogen fuel cells that convert chemical energy of hydrogen directly to electricity with 50-60% electric efficiency, development of bio-hydrogen and bio-methane combined production from biodegradable residues becomes one of the important scientific and technological points (Claassen et al., 1999).

* Corresponding author; E-mail: sadunishvili_tinatin@yahoo.com; Tel: +995 32 520618

A lot of publications have reported on the groundwork for creating bio-hydrogen production systems through photobiological processes performed by photoautotrophic and photoheterotrophic microorganisms. Referring to literature data the maximum photochemical efficiency of photoautotrophic and photoheterotrophic hydrogen production is approximately 1.5% and 10% correspondingly on a full solar spectrum (Arnold et al., 2005). In contrast to phototrophic microorganisms, anaerobic bacteria convert a large variety of carbohydrate sources to hydrogen, CO₂, volatile fatty acids and ethyl alcohol. Since in natural environments (compost, anaerobic digester sludge, soil etc.) hydrogen producing bacteria coexist with methane forming anaerobes which consume above listed metabolites including hydrogen and produce their own end products like methane and CO₂, the most obstacle to obtain hydrogen as the final product of hydrogen fermentation is associated with partition of hydrogen and methane fermentation processes in cost-effective way (Levin et al., 2006). To overcome this drawback some methods like heat treatment of biodegradable wastes and methods based on application of chemicals such as bromethanesulfonate have been successfully tested for the inhibition of methane production at the lab-scale, but it is evident that such approach cannot be used for large scale systems (Zhang et al., 2002).

2. MATERIALS AND METHODS

Research on bio-hydrogen and bio-methane combined production from biodegradable fraction of municipal solid waste described here included the following works: partition of anaerobic process in hydrogen and methane fermentation using low cost chemicals; isolation, study and reveal of alcalophilic and acidophilic thermophilic highly productive hydrogen producing anaerobic bacteria; development of optimum conditions for bio-hydrogen and bio-methane sustainable production and estimation of energy efficiency of two-stage anaerobic digestion process resulting in hydrogen and methane combined production.

For the purpose of methane forming bacteria inhibition in the biodegradable fraction of MSW where mixed microbial cultures of hydrogen producing and methane forming anaerobes were readily available, several low cost chemicals had been tested. For conducting series of experiments 3 l active volume temperature controlled fermenter equipped with on-line pH and gas flow meters was used. Anaerobic fermentation of preliminarily homogenized biodegradable fraction of MSW was conducted at 55°C under oxygen-free nitrogen atmosphere at pH 5.0 and pH 9.0 by using different chemicals. Monitoring parameters were gas composition, gas production rate and cumulative gas production. Gas composition was determined by using Perkin Elmer gas chromatographs with thermal and flame ionization detectors.

With aim to improve bio-hydrogen yield anaerobic alcalophilic thermophilic hydrogen producing bacteria in the genus *Clostridia* were isolated from the soil samples taken in different hot springs of Tbilisi. For isolation of anaerobic thermophilic cellulolytic *Clostridia* inoculums was prepared by mixing 5 g of each soil sample with double-distilled water (1:2) and homogenized in a blender under oxygen-free nitrogen atmosphere. Composition of liquid medium used for bacteria cultivation was as follows (g/l): KH₂PO₄ - 0.4; K₂HPO₄ · 3H₂O - 0.4; NH₄Cl - 1.0; MgCl₂ · 6H₂O - 0.1; yeast extract - 0.2; NaHCO₃ - 6.0; Na₂S · 9H₂O - 0.25; and resazurine- 0.001 was used. To 980 ml of above described solution were added vitamins' and minerals' solutions in 10 ml each. Vitamins' solution was composed of (mg/l) biotin - 2.0; folic acid - 2.0; pyridoxine hydrochloride - 10; thiamine HCl - 5.0; riboflavin- 5.0; nicotinic acid- 5.0; DL-calcium pantothenate- 5.0; vitamin B₁₂- 0.1; *p*-aminobenzoic acid- 5.0; and lipoic acid- 5.0. Mineral solution contained (g/l) nitrilotriacetic acid - 4.5; FeCl₂ · 4H₂O - 0.4; CoCl₂ · 6H₂O - 0.12; NaCl - 1.0; CaCl₂ - 0.02; Na₂MoO₄ · 2H₂O - 0.01; MnCl₂ · 4H₂O - 0.1; ZnCl₂ - 0.1; H₃BO₃ - 0.01; CuSO₄ · 5H₂O - 0.01; and NiCl₂ - 0.02. 50 ml of liquid media was placed in 150 ml volume bottles with both plastic and rubber covers. Filter paper (1% w/v) was introduced there as the only source of carbon. After autoclaving the liquid media and filter paper at 0, 5 atm for 30 min, in different

studies pH was adjusted to 9.0. Growth of cellulose-degrading bacteria at 55⁰ C was determined by visible observation i.e. by production of a yellow/orange pigment and “fluffing” of the filter paper.

Cultures of anaerobic thermophilic saccharolytic *Clostridia* were isolated using the same procedures as for cellulolytic ones. Composition of liquid medium used for isolation of saccharolytic *Clostridia* was the following (g/l): (NH₄)₂HPO₄ – 0.5; K₂HPO₄ – 0.5; MgSO₄ – 0.01; corn extract – 0.25. In different experiments pH was adjusted to 9.0. Glucose, xylose and glucose – xylose mix were used as the only source of carbon.

Pure cultures of above bacteria were obtained by multiple re-seeding methods. They were studied for morphological and biochemical characteristics that included investigation of bacteria growth rate, optimum growth temperature and pH, ability to ferment different cellulosic substrates and monosaccharides, resistance to some antibiotics (ampicillin, actinomycin, streptomycin sulfate and rifampin) and composition of fermentation end-products. Bacteria growth in liquid media was determined by changes in optical density at 600 nm using UV-VIZ spectrophotometer -Lambda EZ. Morphology studies were performed using dyed preparations, liquid cultures and cells grown on agar. Light microscope with resolutions 100/1.25 was used.

In order to develop optimum conditions for bio-hydrogen and bio-methane sustainable production experiments were conducted in plug-flow bioreactor working at thermophilic conditions. To speed up bio-methane production from the metabolite products of hydrogen fermentation such as volatile fatty acids and ethyl alcohol cattle manure was used as the source of methane forming microorganisms.

3. RESULTS AND DISCUSSIONS

3.1. Partition of anaerobic process in hydrogen and methane fermentations

Best results were obtained when 10% solution of sodium hydroxide was used for partition methane fermentation in two separate processes such as hydrogen and methane fermentations. In thermophilic conditions and pH 9.0 bio-hydrogen production started in 5-6 hours and was finished in 8 hours. By the end of the process pH was sharply dropped to 6.8. Cumulative bio-hydrogen production made 82.5 l/kg dry organic matter. Percentage of hydrogen and carbon dioxide in produced bio-hydrogen were – 50.1% and 49.8% correspondingly. Content of methane in bio-hydrogen didn't exceed 0.1 %. Amount of volatile fatty acids (total) obtained in the result of anaerobic hydrogen fermentation reached 7 g/l.

3.2. Isolation, study and cultivation of hydrogen producing anaerobic bacteria

All the strains of saccharolytic and cellulolytic bacteria described here grow at pH range 9.0- 6.9. Saccharolytic *Clostridia* able to grow at thermophilic conditions and pH - 9.0 make the medium equally muddy. Formations of granules are not observed. These bacteria do not grow on the cellulose substrates. When grown in liquid medium containing glucose, xylose and glucose - xylose mix they are of slight brown color. Some of them have light beige pigmentation on glucose containing agar. They form translucent colonies which are of mucus consistency. Cells have a rod-like shape; their spores are round with terminal arrangement. During the spore formation the sporangium swells. The young cells are Gram-positive. Colonies of other alcalophilic thermophilic saccharolytic *Clostridia* grown on agar are of R form, diameter 1 – 2 mm. They are brown with coggled edges. Cells have straight-line or slightly curved rod-like shape. These rods join together and mostly form short chains. Young cells are motile. At the end of the cells large size spores form.

Cells of alcalophilic cellulolytic bacteria isolated under this work are of straight-line form. Spores that much exceed vegetative young cells in size are positioned in terminal arrangement and therefore the young cells are of spindle form. Cellulolytic *Clostridia* grown in liquid medium with cellobiose and cellulose exhibited orange pigmentation.

None of above isolates grows on beef-extract broth. They don't coagulate milk and digest meat. Lipase activity and nitrate reduction are negative. No proteolytic activity was detectable in the cultures' supernatants. Study of antibiotic resistance showed that in the presence of ampicillin, actinomycin, streptomycin sulfate and rifampin in amount of 1 μ g/l fully depress the growth of new isolates.

Testing of microbial consortium composed of above described strains of thermophilic alcalophilic saccharolytic and cellulolytic *Clostridia* showed that hydrogen yield from biodegradable fraction of MSW significantly increases. In particular bio-hydrogen cumulative production makes 104 l/kg dry organic matter. Hydrogen, carbon dioxide and methane percentage in obtained bio-hydrogen was 50.7%; 49.19% and 0.11% correspondingly.

3.3. Optimal conditions for bio-hydrogen and bio-methane sustainable production

Studies showed that optimum hydrogen production can be reached under the following conditions: T – 55°C, pH – 9.0; maximal percentage of dry organic matter and carbohydrates in the bioreactor should not exceed 6% and 5000 γ /ml correspondingly. HRT – 10-12 h. To improve bio-hydrogen cumulative production it is highly desirable to introduce inoculums containing mixed culture of hydrogen producing bacteria in bioreactor at the start of the process.

Studies related to the optimization of bio-methane production from metabolites of hydrogen fermentation show that introduction of inoculums with methane forming bacteria is essential for the rapid start-up of methane production. For these purposes cattle manure was used as a source of methanogenic microorganisms. In series of experiments organic loading rate was variable. Monitored parameters were gas production, composition and concentration of volatile fatty acids in the effluent. In the result of above works it was defined that at thermophilic conditions optimum organic loading rate is 2.3 g total volatile fatty acids/ l. In such conditions cumulative bio-methane production came to 520 l/kg dry organic matter (HRT – 5 days). Methane and carbon dioxide percentage determined in obtained bio-methane was 78.6% and 21.4% correspondingly.

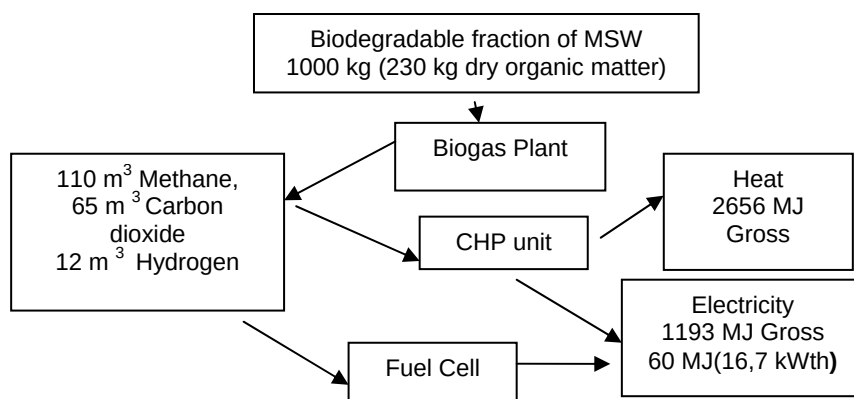


Fig.1. Energy data for two-stage anaerobic digestion of biodegradable fraction of MSW

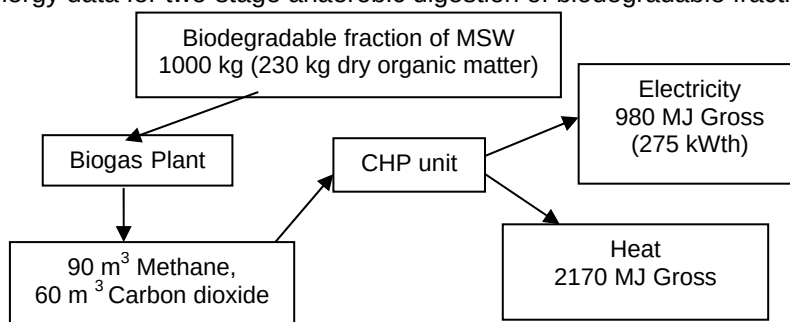


Fig.2. Energy output from biodegradable fraction of MSW with solely methane production

4. CONCLUSIONS

Energy characteristics given in figures 1 and 2 show advantage of two-stage anaerobic digestion process resulting in bio-hydrogen and bio-methane combined production over the single-stage process with solely bio-methane production. In particular, compared to single-stage process heat production increases by 23% under two-stage anaerobic digestion. As for electricity production, it can be increased by 26% when along with CHP unit hydrogen fuel cell is used for electric energy generation.

Thus, implementation of two-stage anaerobic fermentation technology, providing bio-hydrogen and bio-methane combined production from biodegradable fraction of MSW at large scale in biogas plants, will significantly improve the process economy.

ACKNOWLEDGMENTS

This work is supported by the International Science and Technology Center (ISTC), Moscow, Project G -1624. Financing parties: EU and Korea.

REFERENCES

- Arnold L.Demain, Michael Newcomb, and J.H.David Wu. "Cellulase, Clostridia and Ethanol". *Microbiology and Molecular Biology Reviews*, March, 2005, vol. 69, #1, p. 124- 154.
- Claassen PAM, van Lier JB, Lopez Contreeras AM, Van Niel EWJ, Sijtsma L., Stams AJM, de Vries SS, and Weusthuis RA. "Utilization of biomass for the supply of energy carriers". *Appl Microbiol Biotechnol* 1999, 52: 741-755.
- Levin DB, Sparling R, Islam R, Cicek N. "Hydrogen production by *Clostridium thermocellum* 27405 from cellulosic biomass substrates". *International Journal of Hydrogen Energy*, 2006. 31 (11), 1496-1503.
- Ozkan M., Desai S.G., Zhang Y.-H., Stevenson D.M., Beane J., Guerinot M.L., and Lynd L.R. "Characterization of thirteen newly isolated strains of anaerobic, cellulolytic, thermophilic bacteria". *Journal of Industrial Microbiology Biotechnology*, 2001, 27:275-280

AGRICULTURAL RESIDUES FOR ENERGY PRODUCTION AND CARBON STORAGE INTO SOILS: A WIN – WIN OPTION?

Lorenzo Benini^{*1}, Cristian Torri¹, Vittoria Bandini¹, Diego Marazza¹, Leonardo Marotta², Andrea Contin¹

¹ *Interdepartmental Centre for Research in Environmental Sciences - CIRSA, University of Bologna, Via Sant'Alberto 163, 48123 Ravenna, Italy*

² *ENTROPIA S.N.C. di L. Marotta & C*

ABSTRACT

The loss of soil carbon is a global issue that affects the largest terrestrial carbon pool, exerting a large positive feedback on global warming. In this context, agriculture can play an important role, improving energy self-sufficiency and carbon storage. For this reason, the agricultural district of the Ravenna Province (Italy) was considered as study area for evaluating the performance of four different management strategies of agricultural residues (ARs) in terms of energy performances and carbon sequestration. The considered strategies were: A) current management, consisting in electricity production from 10% of ARs, B) bio-charring, consisting in syngas and high recalcitrant carbonaceous matter (bio-char) production through a pyrolysis process and following distribution of bio-char to soils, C) mulching, consisting in the treatment and distribution of the mulch to soils, D) burning with energy recovery for heat production. The overall performances of the strategies were evaluated through an emergy synthesis, and a carbon capture and storage (CCS) assessment was performed using soil carbon modeling and a LCA approach. Data include local information on biomass and environmental parameters and literature data for pyrolysis processes. The results, evaluated on a 30-years period, showed that the bio-charring strategy, when compared to the other strategies, represents the best choice in terms of Environmental Loading Ratio, Environmental Yield Ratio, Emergy Sustainability Index, % Renewability, avoided CO₂ emission (13% of the total yearly GHGs emission due to the consumption in the Ravenna Province) and net Carbon storage into soils. Anyway, this alternative may lead to a decrease in the content of humic carbon in soils; therefore, this aspect has to be carefully evaluated when a decision has to be taken.

Keywords: residual biomass, biochar, emergy synthesis, carbon storage

1. INTRODUCTION

Agriculture is a primary activity by which human societies channel the contemporary flows of renewable energy into products that support societal welfare [Rydberg and Haden, 2006]. The rapid industrialization in agriculture has caused a dramatic increase in the use of fossil energy, a non less dramatic decrease in direct labor requirements, and a substantial increase in gross productivity per unit labor and per unit area [Rydberg and Haden, 2006]. Nowadays, the agricultural production and processing stages are highly dependent on non-renewable resources from the economy such as fossil fuels, goods, electricity, chemical fertilizers, pesticides and herbicides. According to the European Environment Agency [EEA, 2007], agricultural practices exert a significant pressure on natural resources through the consumption of water, the use of chemical fertilizers and pesticides, their influence on soils, water quality and greenhouse gases emission.

A relevant impact, which particularly affects the Mediterranean area but is in general a global issue, is the loss of soil carbon, which at the European level will decrease from

* Corresponding author; E-mail: lorenzo.benini@unibo.it; Tel. +390544937356

88.1 tC/ha of soil organic matter (SOM) to between 84.2 and 85.6 tC/ha in 2080, when IPCC scenarios without changes in technologies and land uses are considered [Smith et al., 2005]. This negative trend exerts a potentially positive feedback on global warming, reduces the fertility of soils and thus indirectly increases the use of fertilizers for maintaining the productivity.

Because of the important role of agricultural activities at global scale, and without entering the discussion about the suitability of the current global agricultural systems, from personal lifestyles (e.g. vegetarianism) to social inequalities (e.g. overproduction and food destruction), this paper aims to compare four different strategies of agricultural residues (ARs) management, in terms of efficiency of resources use, soil carbon evolution (total and humic components) and relative greenhouse gases (GHGs) emission, on a 30-years scale. Because of the data availability, the Ravenna Province, a relatively small area in northern Italy, has been considered as a case study.

In particular, the emergy synthesis approach is used in order to evaluate the performances of the considered alternatives in terms of resources use, considering that the emergy evaluation allows for the comparison, on a common basis, of processes producing similar products, but through different means. This approach may offer a more complete picture of the role of agriculture in the biosphere and of human economies, by calculating the total work contributed by both natural and economic systems to generate agricultural products, measured on a common basis and in one kind of energy. Emergy evaluations thus provide a more universal assessment of the total work requirements of agricultural production than other methods [Rydberg and Haden, 2006]. A soil carbon modeling [Benini and Torri, 2010] and a life cycle assessment approach [Roberts et al., 2010] were used for quantifying total and humic soil carbon evolution and GHGs emissions due to the considered alternatives, in order to highlight both the carbon storage efficiency and the net effect on the humic component of soils, the latter being an important agronomic parameter.

2. MATERIALS AND METHODS

2.1 Agricultural district of Ravenna Province

Agricultural areas in the Ravenna Province represent more than 70% of the total land use, with approximately 20% of orchards and 50% of croplands. The total amount of agricultural residues (ARs) within the Ravenna Province is equal to $4.1 \cdot 10^5$ tons per year, as evaluated by Benini and Torri [2010], where residues from cropping activities (corn stover) are equal to 78% of the total amount. The residual biomasses that are considered to be representative of the different types of cultivations are: “corn stover and similar” for the cropping areas and “fruit pruning”, for orchards. Agriculture in the Ravenna district is an highly industrialized system which requires an important input of non-renewable resources, implying an high use of pesticides and fertilizers (Table 1).

2.2 Alternatives for agricultural residues management

The considered strategies are: A) current management; B) bio-charring; C) mulching; D) direct burning. The strategies were supposed to be carried out, without any modification, for a period of 30 years. The current management strategy (A) consists in the management of ARs which is being carried out in the Ravenna Province, with 10% of ARs used for electricity production and 90% that are open burned. The bio-char strategy (B) consists of the collection, drying and pyrolysis of ARs, in order to produce syngas or bio-oil and bio-char; then, the bio-char is applied to soils and the fuels are burnt in order to replace fossil fuels for producing heat or electricity. The mulching strategy (C) consists of the collection, drying and chipping of ARs and the distribution of the mulch in the soils, in

order to improve the physical features of soils and increase the input of organic matter. The last strategy (D) consists of the direct burning of ARs with the recovery of heat.

2.3 Soil carbon capture and storage (CCS)

According to Roberts et al. [2010] the net effect of the distribution of bio-char to soils is carbon negative and this is due to: a) the reduction of fertilizers needed; b) the use of the syngas/bio-oil for heating purposes and c) the stocking of carbon into soils, in the form of bio-char. Benini and Torri [2010] have extended this results by including a soil carbon modeling, with the aim of introducing the decay of the carbon content into soils and of evaluating the dynamic evolution of the humic and total carbon into soils under a specific ARs management strategy.

In this work the greenhouse gases emissions for each of the considered strategies have been calculated through a Life Cycle Assessment (LCA), by the sum of the emissions related to the energy consumption activities, the avoided GHGs emissions deriving from the production of energy through ARs burning and the CO₂ emissions due to the depletion or enrichment of the soil carbon pool. The results have been then referred to a baseline condition (the worst management strategy, which is similar to the A strategy but does not include energy recovery), obtaining a comparison between alternatives regarding the potential GHGs emissions reduction on a time span of 30 years. For each of the considered alternatives the data on the dynamic evolution of the humic and total carbon into soils have been derived from the results proposed by Benini and Torri [2010] for the same study area. Each strategy has been compared in terms of carbon capture and storage (CCS), soil total carbon and soil humic carbon accumulation/depletion.

The worst possible strategy (which corresponds to A strategy without energy recovery) is defined as the reference for the evaluation of the storage or depletion of carbon in soils [Benini and Torri, 2010], therefore its variation in the total carbon content (ΔC_{TOT}) and humic carbon content (ΔC_{HUM}) are equal to zero.

2.4 Emergy synthesis

Emergy is a unit of measure introduced by Odum [1996], to take into account all the resources (natural and manufactured) sustaining a system. It is the quantity of equivalent solar energy needed directly or indirectly to obtain a product or sustain a given process. The emergy accounting approach provides a scientific measure of the global environmental support that is needed for a process to be viable and sustainable [Ulgiati, 2001].

Units are solar emjoules (sej). Each flow of energy or matter is transformed in its emergy equivalent through the use of a sej/unit conversion factor (Transformity).

Emergy flows are grouped into renewable (R), local non-renewable (N) and imported emergy (F). The sum of R, N and F flows represents the total yield (Y) of the system.

Emergy evaluation is accomplished in five main stages: (1) identification of the frontiers of the system; (2) realization of a system diagram; (3) analysis of input and output energy flows in the system; (4) calculation of emergy indices and (5) interpretation of those indices [Brown and Ulgiati, 2004; Cavalett and Ortega, 2009].

The following emergy indexes have been calculated: the Emergy yield ratio (EYR), which is a measure of the local contribution to the system in terms of local resources; the Environmental loading ratio (ELR), which evaluates how far from its natural structure is an ecosystem, or the pressure exerted on the natural environment by a process; the %Ren, which represents the percentage of renewable flows among all the emergy flows of a system; the Emergy index of sustainability (ESI) and the Emergy investment ratio (EIR) [Brown and Ulgiati, 2004].

The frontiers of the system in this work embrace the whole agricultural system of the Ravenna Province, from the cultivation of crops and fruits to the management of

agricultural residues. The produced food exits from the system and its processing, distribution and consumption are not included in the study. On the contrary, the collection and management of agricultural residues are included in the system, and four different management strategies are explored for these residues.

An emergy diagram has been realized in order to describe the whole agricultural systems and the strategies evaluated in this work (Figure 1).

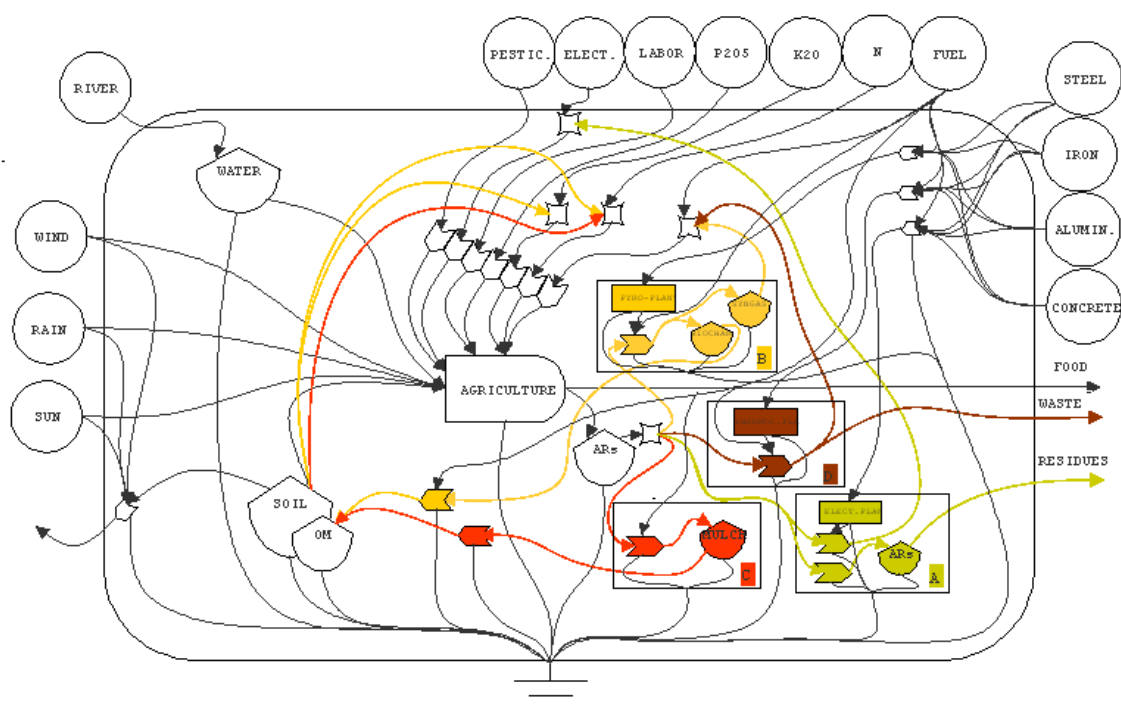


Figure 1. Emergy diagram of the agricultural system of the Ravenna district. The letters represent the 4 different management strategies for ARs: A- Current management; B – Biochar production; C- Mulching; D- Direct burning.

2.5 Relevant indicators selection and aggregation

In order to identify the best alternative among the assessed strategies, the indicators related to the results of the emergy synthesis, the soil carbon storage and the avoidance and sequestration of greenhouse gases have been represented in a radar plot. Because of the absence of reference targets for most of the indicators, the normalization was carried out through a min-max normalization method [OECD, 2008], where the scale used for comparing the alternative is, for each indicator, bounded by the best and worst value obtained by the alternatives. Moreover, a multi-criteria comparison using both the arithmetic average and the Euclidean distance has been performed.

3. RESULTS AND DISCUSSION

3.1 Evolution of carbon storage in soil and CCS efficiency

As anticipated in paragraph 2.3, the variations in the total carbon content (ΔC_{TOT}) and humic carbon content (ΔC_{HUM}) for A strategy are equal to zero. The D strategy, which foresees the direct burning of ARs, with no return of biomass to soils, also scores zero on both indicators.

According to Benini and Torri [2010], the distribution of biochar to soil (B strategy) allows for a strong increase in the storage of C_{TOT} , but has a negligible effect on C_{HUM} , because of the high-recalcitrant nature of the C embodied in biochar. The mulching

strategy (C) gives a slightly lower increase in C_{TOT} (0.36 tC/year instead of 0.53 tC/year for B strategy, mean values over 30 years), but contributes to the increase of C_{HUM} (0.15 tC_{HUM}/year instead of 0.02 tC_{HUM}/year for B strategy).

The potential GHGs capture or avoidance, compared to the worst theoretical condition, shows similar results for strategies B, C and D and is relatively small for strategy A (Table 2). This is due to the fact that alternative A, which is representative of the current management of ARs in the Ravenna Province, uses only 10% of the available ARs for producing electricity, thus slightly gaining from the energy recovery from biomasses and the consequent reduction in the use of other fossil fuels. The alternatives B and C present a comparable efficiency of soil carbon capture and storage on average over 30 years, showing that the traditional management alternative of mulching is not far from the technological solution (B).

3.2 Emergy assessment of the agricultural system

An emergy diagram has been realized in order to describe the whole agricultural systems and the four strategies evaluated in this work (Figure 1). Then, based on the flows represented in the diagram, the emergy evaluation table has been compiled (Table 1). This table has been divided in the main phases of the ARs treatment.

Table 1. Emergy evaluation table for the 4 management strategies.

Item	A	B	C	D	Unit	sej unit-1	Ref	A - Actual management	B - Biochar strategy	C - mulching strategy	D - Direct burning
<i>Agricultural phase</i>											
Renewable inputs											
Sun	1.98E+14	1.98E+14	1.98E+14	1.98E+14	J/Year	1.00E+00	Def.	1.98E+14	1.98E+14	1.98E+14	1.98E+14
Evapotranspired rain (chemical potential energy)	4.32E+15	4.32E+15	4.32E+15	4.32E+15	J/year	3.06E+04	a	1.32E+20	1.32E+20	1.32E+20	1.32E+20
Wind	1.09E+16	1.09E+16	1.09E+16	1.09E+16	J/Year	2.51E+03	a	2.74E+19	2.74E+19	2.74E+19	2.74E+19
River geopotential	3.66E+14	3.66E+14	3.66E+14	3.66E+14	J/year	4.66E+04	a	1.70E+19	1.70E+19	1.70E+19	1.70E+19
Non renewable inputs											
Loss of topsoil in mountain areas	3.35E+11	3.35E+11	3.35E+11	3.35E+11	J/year	1.24E+05	b	4.15E+16	4.15E+16	4.15E+16	4.15E+16
Loss of SOM due to agricultural practices	2.15E+12	0.00E+00	0.00E+00	2.15E+12	J/year	1.24E+05	b				
Diesel	3.1E+15	3.06E+15	3.06E+15	3.06E+15	J/year	6.58E+04	c	2.01E+20	2.01E+20	2.01E+20	2.01E+20
Electricity	5.3E+14	5.28E+14	5.28E+14	5.28E+14	J/year	3.18E+05	d	1.68E+20	1.68E+20	1.68E+20	1.68E+20
Pesticides	6.57E+06	6.57E+06	6.57E+06	6.57E+06	kg/year	2.48E+13	b	1.63E+20	1.63E+20	1.63E+20	1.63E+20
Nitrogen in fertilizer	1.53E+07	1.53E+07	1.53E+07	1.53E+07	kg/year	6.38E+12	e	9.75E+19	9.75E+19	9.75E+19	9.75E+19
Phosphorus in fertilizer	2.83E+06	2.83E+06	2.83E+06	2.83E+06	kg/year	6.55E+12	b	1.85E+19	1.85E+19	1.85E+19	1.85E+19
Potash in fertilizer	3.36E+06	3.36E+06	3.36E+06	3.36E+06	kg/year	2.92E+12	b	9.81E+18	9.81E+18	9.81E+18	9.81E+18
Steel for machinery	3.33E+06	3.33E+06	3.33E+06	3.33E+06	kg/year	1.13E+13	b	3.76E+19	3.76E+19	3.76E+19	3.76E+19
Farm buildings	6.31E+06	6.31E+06	6.31E+06	6.31E+06	\$/year	3.85E+12	f	2.43E+19	2.43E+19	2.43E+19	2.43E+19
Local labor	6.94E+02	6.94E+02	6.94E+02	6.94E+02	year/yr	1.07E+16	b	7.43E+18	7.43E+18	7.43E+18	7.43E+18
Products and by-products											
Residual biomass	4.10E+05	4.10E+05	4.10E+05	4.10E+05	t/year	0.00E+00	b	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cereals and legumes	6.05E+05	6.05E+05	6.05E+05	6.05E+05	t/year	varies	j	3.88E+20	3.44E+20	4.38E+20	4.26E+20
Fruit and grapes	6.44E+05	6.44E+05	6.44E+05	6.44E+05	t/year	varies	j	4.14E+20	3.66E+20	4.66E+20	4.54E+20
<i>Treatment of residues phase</i>											
Transport (both to and from the fields)											
Steel in trucks for transport	1.44E+03	2.87E+04	2.87E+04	1.44E+04	kg/year	1.13E+13	b	1.62E+16	3.24E+17	3.24E+17	1.62E+17
Labor for transport	3.20E+00	6.41E+01	6.41E+01	3.20E+01	year/yr	1.07E+16	b	3.43E+16	6.85E+17	6.85E+17	3.43E+17
Diesel fuel for transport	1.23E+12	2.46E+13	2.46E+13	1.23E+13	J/year	6.58E+04	c	8.10E+16	1.62E+18	1.62E+18	8.10E+17
Crushing											

Diesel for machinery	0.00E+00	1.32E+13	1.32E+13	1.32E+13	J/year	6.58E+04	c	0.00E+00	8.69E+17	8.69E+17	8.69E+17
Pyrolysis											
Steel	0.00E+00	1.68E+08	0.00E+00	0.00E+00	g/year	2.77E+09	g	0.00E+00	4.64E+17	0.00E+00	0.00E+00
Iron	0.00E+00	2.20E+06	0.00E+00	0.00E+00	g/year	2.77E+09	g	0.00E+00	6.10E+15	0.00E+00	0.00E+00
Aluminium	0.00E+00	1.10E+06	0.00E+00	0.00E+00	g/year	1.63E+10	h	0.00E+00	1.80E+16	0.00E+00	0.00E+00
Concrete	0.00E+00	5.28E+08	0.00E+00	0.00E+00	g/year	5.08E+08	g	0.00E+00	2.68E+17	0.00E+00	0.00E+00
Products and by-products											
Biochar	0.00E+00	1.15E+05	0.00E+00	0.00E+00	t/year						
Syngas	0.00E+00	1.89E+15	0.00E+00	0.00E+00	J/year						
Mulch	0.00E+00	0.00E+00	4.10E+05	0.00E+00	t/year						
<i>Use of treated residues phase</i>											
Current management - thermal plant											
Iron and Steel	1.54E+07	0.00E+00	0.00E+00	0.00E+00	g/year	2.77E+09	g	4.26E+16	0.00E+00	0.00E+00	0.00E+00
Labor and services	3.52E+00	0.00E+00	0.00E+00	0.00E+00	year/yr	2.49E+16	i	8.75E+16	0.00E+00	0.00E+00	0.00E+00
Concrete	3.78E+08	0.00E+00	0.00E+00	0.00E+00	g/year	5.08E+08	g	1.92E+17	0.00E+00	0.00E+00	0.00E+00
Direct burning											
Iron and steel	0.00E+00	0.00E+00	0.00E+00	4.44E+08	g/year	2.77E+09	g	0.00E+00	0.00E+00	0.00E+00	1.23E+18
Copper	0.00E+00	0.00E+00	0.00E+00	6.00E+06	g/year	2.00E+09	h	0.00E+00	0.00E+00	0.00E+00	1.20E+16
Concrete	0.00E+00	0.00E+00	0.00E+00	5.58E+08	g/year	5.08E+08	g	0.00E+00	0.00E+00	0.00E+00	2.83E+17
Products and by-products											
Electricity (from biomass)	2.38E+14	0.00E+00	0.00E+00	0.00E+00	J/year						
Thermal energy	0.00E+00	1.89E+15	0.00E+00	5.90E+15	J/year						
Increase in SOM	0	7.65E+15	8.72E+15	0	J/year						
Nitrogen fertilizer	0	3.92E+06	-3.77E+06	0	kg/year						
Phosphorus fertilizer	0	1.78E+06	0	0	kg/year						
Potash fertilizer	0	3.35E+06	0	0	kg/year						
Balance											
Overall diesel consumption	3.1E+15	1.2E+15	3.1E+15	3.1E+15	J/year	6.6E+04	c	2.02E+20	7.85E+19	2.03E+20	2.02E+20
Overall electricity consumption	2.9E+14	5.3E+14	5.3E+14	5.3E+14	J/year	3.2E+05	d	9.22E+19	1.68E+20	1.68E+20	1.68E+20
Overall N fertilizer	1.53E+07	1.14E+07	1.90E+07	1.53E+07	kg/year	6.4E+12	e	9.75E+19	7.25E+19	1.21E+20	9.75E+19
Overall P fertilizer	2.83E+06	1.05E+06	2.83E+06	2.83E+06	kg/year	6.6E+12	b	1.85E+19	6.89E+18	1.85E+19	1.85E+19
Overall K fertilizer	3.36E+06	1.17E+04	3.36E+06	3.36E+06	kg/year	2.9E+12	b	9.81E+18	3.41E+16	9.81E+18	9.81E+18
Overall SOM loss	2.48E+12	-7.65E+15	-8.72E+15	2.48E+12	J/year	1.2E+05	b	3.08E+17	9.49E+20	-1.08E+21	3.08E+17

a) Folio 2; b) Brown and Ulgiati, 2004; c) Bastianoni et al., 2009 d) Bandini, 2010; e) Ortega et al., 2005; f) NEAD database; g) Haukoos, 1994; h) Lapp, 1991; i) Brown and Ulgiati, 2002; j) this work

While some flows remain constant for all the strategies, others change significantly. In particular, the flows of organic matter in soil differ among the strategies, as well as the energy production, both from fossil fuels and biomass, and consumption. Moreover, the flows of N, K and P fertilizers differ among the scenarios, because of the contribution in minerals provided by the distribution of biochar to soils. The distribution of mulch to soils results in an increased need for N fertilizers in order to maintain the correct C/N ratio. This requirement results in a significant energy flow, which affects the energy indices calculated for this strategy.

Strategies B and C have a null flow of local non renewable energy (N), due to the fact that they provide the soil with more organic matter than is yearly lost.

The transformities of the agricultural products in the four strategies show that the productive system is more efficient in the B strategy, with less resources per unit of product, followed by the A strategy.

Regarding the values of the emergy indices, %Ren varies from 17% (strategies C and D) to 21% (strategy B): these values are in general representative of an highly industrialized agricultural system, with the biochar strategy only slightly better than the other ones. ESI values are all lower than 1, again typical values for highly industrialized systems [Brown and Ulgiati, 2004].

ELR values indicate moderate environmental impacts, showing the best performance of the biochar strategy and the worst performance of the mulching strategy. These low values of ELR may derive from the positive feedback provided to the system by the exploitation of the agricultural residues.

The emergetic contribution of the purchased fertilizers (N in particular) strongly affects the total values of emergy flows, because of their high transformity. Therefore, a change in the origin of these fertilizers (from purchased to internally produced as by-products of cattle-breeding) would result in a strong increase in the overall renewability of the system and in its reliance on local resources.

3.3 Supporting the decision making process through relevant indicators

The indicators that are considered to be relevant for supporting the decision making process on the ARs management have been represented in the radar plot shown in Figure 2. This radar plot has the advantage of presenting the results in a very communicative way, but it has to be interpreted as a relative comparison among four alternatives, not as an absolute judgement on the performance of each alternative. For this reason, it has to be coupled with the absolute values shown in Table 2. From that table it is possible to see that the best alternative for all but the C_{HUM} indicator is the biochar strategy (B), indicating that this technological alternative could be able to reduce the pressures exerted by the agricultural system on the ecosystems, in terms of resources consumption, total soil carbon and recovery GHGs recovery. This strategy allows for the recovery of 13% of the yearly GHGs emissions due to the energy consumptions in the Ravenna Province [Provincia di Ravenna and CIRSA, 2009]. The results of the multi-criteria analysis show the net dominance of the B strategy when compared to the others as well.

Table 2. Selected indices results for the assessed management strategies of ARs

		Unit	A - Current management	B - Biochar strategy	C - mulching strategy	D - Direct burning
R	renewable emergy flows	sej/year	1.49E+20	1.49E+20	1.49E+20	1.49E+20
N	non renewable local emergy flows	sej/year	3.08E+17	0.00E+00	0.00E+00	3.08E+17
F	goods, labor and services from economy	sej/year	6.52E+20	5.60E+20	7.54E+20	7.30E+20
Y	total eMergy	sej/year	8.02E+20	7.09E+20	9.04E+20	8.80E+20
EYR	eMergy yield ratio (Y/F)		1.23	1.27	1.20	1.20
ELR	Environmental loading ratio (N+F)/R		4.37	3.75	5.05	4.89
ESI	Emergy index of sustainability (EYR/ELR)		0.28	0.34	0.24	0.25
%R	Percentage of renewable emergy	%	19%	21%	17%	17%
EIR	Emergy Investment ratio		4.36	3.75	5.05	4.88
Tr. Food	Transformity Food	sej/t	6.42E+14	5.68E+14	7.24E+14	7.05E+14
CO ₂ eq	Avoided CO ₂ eq per year (30 years average)	tCO ₂ eq/year	5.44E+03	3.71E+05	1.75E+05	3.37E+05
CTOT	Total Soil Carbon storage (30 years average)	tC/year	0.00	0.53	0.36	0.00
CHUM	Humic Soil Carbon storage (30 years average)	tC/year	0.00	0.02	0.15	0.00

Another interesting result that arises from the coupling of emergy synthesis and the evaluation of soil carbon capture and storage is the quantification of the transformity of the GHGs capture and storage mechanism, expressed as sej/tCO₂eq. The results for the strategies that store carbon on soils (B and C strategies) are, respectively $1.91 \cdot 10^{15}$ and

$5.18 \cdot 10^{15}$ sej/tCO₂eq. These values can be an interesting starting point for the comparison among different carbon capture and storage technologies.

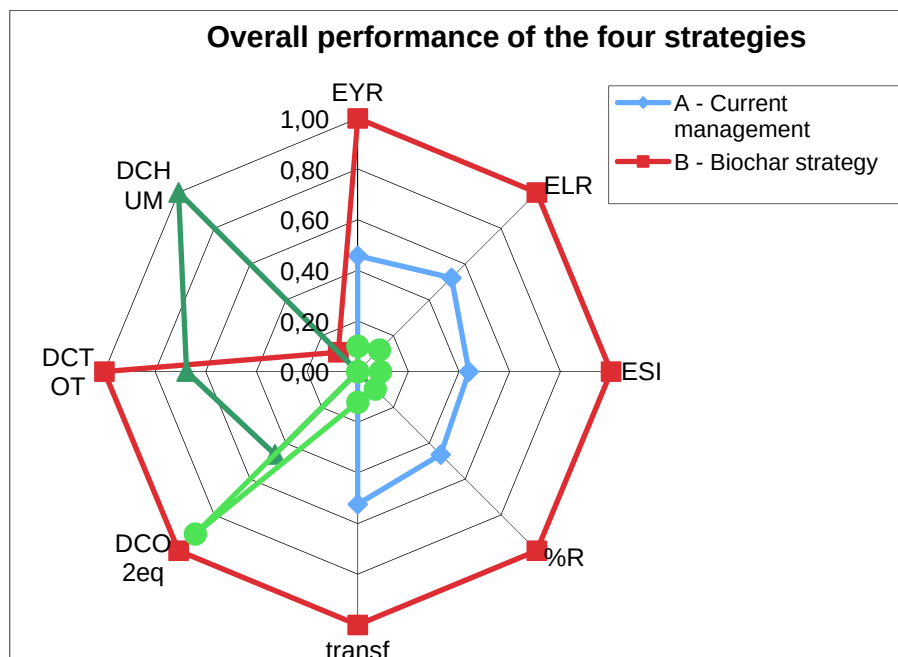


Figure 2. Selection of relevant indicators for the four assessed management strategies for ARs.

4. CONCLUSIONS

This work coupled emergy synthesis with greenhouse gases accounting, using results of soil modeling and life cycle assessment carried out on the same area [Benini and Torri, 2010], under similar alternatives of agricultural residues management. By doing so, it was possible to assess how different strategies of residues management perform with respect to the considered indicators; it was also possible to evaluate, for the first time, the transformity of the carbon capture and storage obtainable by agricultural activities, expressed in sej/tCO₂eq, ranging from $1.19 \cdot 10^{15}$ to $5.18 \cdot 10^{15}$ sej/tCO₂eq.

Looking at the general system theory and considering the relevance of the climate change issue, the biochar strategy seems to be the best alternative for agricultural residues management in the Ravenna Province. Anyway, before confirming that this alternative can represent a sound and suitable solution for real applications, it has to be considered that the results of soil modeling are strictly dependent on environmental parameters (among which soil composition, temperature and precipitations) and that other evaluations have to be carried out, especially on the effect of the substitution between humic carbon and biochar in soils, in order to get a better understating of possible side impacts of this strategy on agricultural systems.

ACKNOWLEDGEMENTS

We would like to thank prof. Sergio Ulgiati for his friendship and support to our work.

REFERENCES

- Bandini, V., 2010. Doctoral Thesis. *Applicazione di strumenti e metodi per la gestione ambientale di un territorio vasto - Sviluppo di un sistema di gestione ambientale in un ente pubblico secondo lo schema europeo "EMAS" e analisi di un sistema energetico territoriale*. University of Bologna
- Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. "The solar transformity of petroleum fuels". *Ecological modelling* 220 (2009) 40–50
- Benini L. and Torri C. "Soil organic carbon enrichment and carbon sequestration from residual biomass through pyrolysis and bio-char application to soils: preliminary assessment in the Ravenna province countryside". *18th European Biomass Conference and Exhibition, Lyon, 3-7 May, 2010, Book of proceedings*.
- Brown M.T., Ulgiati, S., 2002. "Emergy evaluations and environmental loading of electricity production systems". *Journal of Cleaner Production* 10 (2002) 321–334
- Brown MT, Ulgiati S. *Emergy analysis and environmental accounting*. *Encyclopedia of Energy* 2004;2:329–54
- Cavalett O., Ortega E., 2009. "Emergy, nutrients balance, and economic assessment of soybean production and industrialization in Brazil". *Journal of Cleaner Production* 17 (2009) 762–771
- Centre for Environmental Policy, University of Florida. *National Environmental Accounting Database (NEAD)*, available at <http://cep.ees.ufl.edu>
- European Environment Agency (EEA). *Europe's environment. The fourth assessment. 2007*, European Environment Agency, Copenhagen;
- Haukoos DS. *Sustainable architecture and its relationship to industrialized building*. A thesis presented to the Graduate School of the University of Florida in partial fulfillment of the requirements for the Degree of master of Science in Architectural Studies. Department of Environmental Engineering Science, University of Florida, Gainesville, FL, 1995
- Lapp CW. *Emergy analysis of the nuclear power system in the United States*. Class report, EES 6916, Department of Environmental Engineering Science, University of Florida, Gainesville, FL, 1991
- Odum HT, 2000. *Folio #2: Emergy of global processes*. Gainesville: Center for Environmental Policy, University of Florida; 2000.
- Odum HT. *Environmental accounting: emergy and environmental decision making*. New York, NY, USA: Wiley; 1996
- Organization for Economic Cooperation and Development (OECD), Joint Research Center of European Commission. *Handbook on constructing composite indicators, methodology and user guide*, 2008; ISBN 978-92-64-04345-9
- Ortega E, Cavalett O, Bonifacio R, Watanabe M. "Brazilian soybean production: emergy analysis with an expanded scope". *Bulletin of Science, Technology & Society* 2005;25(4):323–34
- Provincia di Ravenna e CIRSA, 2009. *Piano Energetico Provinciale: Quadro Conoscitivo, Sintesi del Quadro Conoscitivo*, Piano d'Azione ed Appendice.
- Roberts K. G.; Gloy B. A.; Joseph S.; Scott N. R.; Lehmann J. "Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential". *Environ. Sci. Technol.* 2010, 44 (2), 827–833; DOI 10.1021/es902266r
- Rydberg T.; Haden A.C. "Emergy evaluations of Denmark and Danish agriculture: Assessing the influence of changing resource availability on the organization of agriculture and society". *Agriculture, Ecosystems and Environment* 2006, 117, 145–158;
- Smith J.; Smith P.; Wattenbach M.; Zaehle S.; Hiederer R.; Jones R. J. A.; Montanarella L.; Rounsevell M. D. A.; Reginster I.; Ewert F. "Projected changes in mineral soil carbon of European croplands and grasslands, 1990–2080". *Global Change Biology* 2005, 11, 2141–2152; DOI: 10.1111/j.1365-2486.2005.01075.x
- Ulgiati, S., 2001. "A Comprehensive Energy and Economic Assessment of Biofuels: When "Green" Is Not Enough". *Critical Reviews in Plant Sciences*, 20(1): 71–106 (2001)

INTEGRATED ANALYSIS OF SUSTAINABILITY

Zucaro A., Buchan K., Mellino S., Viglia S. and Ulgiati S.

ENERGY AND ENVIRONMENTAL PERFORMANCE OF NATIONAL AGRICULTURAL SECTORS. ITALIAN AND SCOTTISH CASE STUDIES

Fahd S., Fiorentino G., Mellino S., Rótolo G. and Ulgiati S.

ENERGY, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF NON-FOOD USE OF BRASSICA CARINATA

Markussen M. V. and Østergård H.

VIABILITY OF BIOFUELS AS INFLUENCED BY AGRICULTURAL PRODUCTION SYSTEM

Cavalett O., D'Angelo S., Franzese P. P.

ENERGY AND EMERGY EVALUATIONS OF AGRICULTURAL AND FARMING PRODUCTION SYSTEMS IN THE TOLEDO RIVER BASIN (BRAZIL)

Bright R. M., Strømman A. H., Peters G. P.

RADIATIVE FORCING IMPACTS OF BOREAL FOREST BIOFUELS: A DYNAMIC STUDY FOR NORWAY IN LIGHT OF ALBEDO

Marotta L., Benini L., Vogli L., Bandini V., Deandrea G., and Marazza D.

INDICATORS, EMERGETIC THRESHOLDS AND CONSTRAINTS FOR COASTAL SPATIAL PLANNING AND MANAGEMENT

Bayod-Rújula A. A., Martínez A.

DEFOSSILIZATION: LINKING ENERGY CONSUMPTION AND RENEWABLE GENERATION

Philomena A. L.

HYDROELECTRICITY AS ALTERNATIVE IS A REAL CLEAN ENERGY? THE BELO MONTE CASE

Andersen Chinbuah A.

INTERNATIONAL COMPARISON OF THE EXOSOMATIC ENERGY METABOLIC PROFILE OF DEVELOPED ECONOMIES

Marques A., Rodrigues J. and Domingos T.

THE CIRCULAR FLOW OF CO₂ EMISSIONS EMBODIED IN INTERNATIONAL TRADE

Pasquini A., Tedeschi A.

SOCIETY PERCEPTION OF ENVIRONMENTAL RISKS

ENERGY AND ENVIRONMENTAL PERFORMANCE OF NATIONAL AGRICULTURAL SECTORS. ITALIAN AND SCOTTISH CASE STUDIES

Amalia Zucaro^{*1}, Kevin Buchan², Salvatore Mellino¹, Silvio Viglia¹ and Sergio Ulgiati¹

¹ Parthenope University of Naples, Department of Environmental Sciences,
Naples, Italy

² Macaulay Land Use Research Institute, Craigiebuckler, Aberdeen, U.K.

ABSTRACT

Agricultural systems are a crucial interface between human societies and nature, in that they “amplify” the human-controlled investments by concentrating natural energies of sun, rain and nutrients and make them converge to food production. Understanding the energy and environmental performance of agricultural systems is of paramount importance for proper management and sustainable use of photosynthesis. Moreover, agriculture always had, and still has, a multifunctional role by providing society with food, construction materials, fibers, chemicals, bioenergy, environmental services and landscape protection. More than direct energy production, the indirect energy savings associated to proper management as well as to biomaterials might become an important aspect of such a multifunctional role. Even if GDP, labor and energy expenditures associated to agriculture are unlikely to ever represent a large fraction of the total performance of a national developed economy, yet the role of such a sector goes much beyond the actual food production and calls for higher attention by concerned policy makers. The evaluation of the dynamics and performance of agricultural systems must be carefully investigated from different points of view (energy, economic, environmental, social) in order to point out how the system and its main driving forces are evolving over time and how can they support a national economy. In this study we compare the agricultural systems of Scotland and Italy at different time scales, by means of an integrated analysis model, SUMMA (*SUstainability Multimethod Multiscale Assessment*) capable to take into account the different dimensions of the investigated systems. The final goal was to understand what are the steps of the process that are characterized by the lowest performances as well as how the system can be made more robust and resilient in spite of the existing problems (among which increasing energy and resource prices, decreasing land quality, and decreasing marginal productivity). The improvement of agricultural activity requires as a prerequisite the identification and optimization of crucial steps, with special focus on energy and resource use.

Keywords: Life Cycle Assessment, Integrated Evaluation, Agriculture, Emergy

1. INTRODUCTION

The dynamics and performance of agriculture can be evaluated in many ways by means of economic, social and environmental parameters. Life Cycle Assessment (LCA), described in the ISO norms 14040/2006 and 14044/2006, is an invaluable tool also for the agricultural and ecological management. In order to implement a full LCA, several methods are combined into a comprehensive and complete approach “*SUstainability Multimethod Multiscale Assessment*” (SUMMA) (Ulgiati *et al.*, 2006, Ulgiati *et al.*, 2010). The main idea of SUMMA is that in no circumstance can a single method be sufficient to provide global understanding on environmental impact assessment, and that analyses based on only one approach invariably end up providing partial and sometimes even counterproductive indications. The present study analyzes the performance of the Scottish and Italian agricultural sectors at national scales over the last two decades, in order to

*Corresponding author; E-mail: amalia.zucaro@uniparthenope.it; Tel: +39 3393567715

calculate and compare performance indicators that can be usefully extended to other national and local systems..

2. MATERIALS AND METHODS

The performances of national Italian and Scotland agricultural systems were investigated in different years (1985, 1993, 2002 and 2006 for the Italian agriculture, and 1991, 2001, and 2007 for the Scottish one) in order to assess and compare sustainability changes over time.

2.1 The investigated systems

The high soil fertility, good climate conditions and water abundance, that characterize the Italian agriculture enable the production of a large variety of high-quality fruit and vegetable products. The agricultural sector in Italy still is a very important economic, environmental and social activity in support of a large fraction of people directly involved in agricultural production and agro-industrial food manufacture. Of course, the Italian agricultural activity is far from reaching any high share of the Italian GDP (agricultural GDP is only 2% of the national GDP). The northern part of Italy produces primarily grains, sugar beets, soybeans, meat, and dairy products, while southern agriculture is specialized in fruits, vegetables, olive oil, wine, and durum wheat. The average, Italian-farm size is only seven hectares (ISTAT, 2006), most of which run as family enterprises. Very likely due to these characteristics, agricultural work force in Italy is relatively very large (about 1 million employed in farming), accounting for approximately the 4% of total national work force, in the year 2006.

On the other hand, Scotland, located in the north of Britain, is very well known for its beautiful and mountainous landscape and also for its forests, rivers and lakes. Its climate is affected by the Gulf Stream and also for this reason wildlife and flora are very diverse. Almost 5,100,000 of people live in the country with a population density of 65.6 people per square kilometers. About 65,000 people are directly employed in agriculture and it is estimated that more or less 250,000 jobs (1 in 10 of all Scottish jobs) derive from this sector.

2.2 Method

SUMMA (*SUstainability Multimethod Multiscale Assessment*) is based on the joint application of different evaluation methods, which can be divided in two broad categories: those that are focused on the amount of resources supplied ("upstream" methods), and those that deal with the consequences of the system's emissions ("downstream" methods). Each individual assessment method is applied according to its own set of rules. The 'upstream' methods are concerned with the input flows, and account for the use and/or depletion of environmental resources (minerals, energy, natural capital and environmental services), while the 'downstream' methods are applied to the outputs, and look at the environmental consequences of the emissions. The calculated impact indicators are then interpreted within a comparative framework, in which the results of each method are set up against each other and contribute to providing a comprehensive picture on which conclusions can be drawn.

Upstream methods selected in this approach are *Material Flow Accounting*, *Embodied Energy Analysis* and *Emergy Accounting*, while the downstream methods are based on the inventory of main airborne and waterborne emissions estimated according to CORINAIR (2007). The main impacts were modelled with reference to the *CML2 baseline 2000* framework (Leiden, 2000). Detailed description of each method can be found in Ulgiati *et al.* (2006, 2010).

1.2.1 Systems diagram

The generic system diagram of an agricultural system is shown in Figure 3a, with symbols explained in Figure 3b. The renewable sources (sun, rain, wind and deep heat) are shown in the left side of the diagram. These sources go directly in support of the whole investigated system. In addition to renewable flows, further imported flows from the main economy (fossil fuels, fertilizers, pesticides, electricity, goods, machinery and labor) support agricultural production. These flows are shown as entering from the top of the system diagram. The “assets” symbol represents the most typical infrastructure of agricultural systems (barns, storage buildings, irrigation system, etc).

Agricultural products are exported and the market pays for them. Such money adds up to the total budget of the agricultural sector, indicated in the diagram as a money storage. The agricultural budget is mainly composed by the money that farm workers receive as an income of productive activities (products sold), as well as contribution from external investments. Money is used to pay for the resources imported and that are needed to support the system.

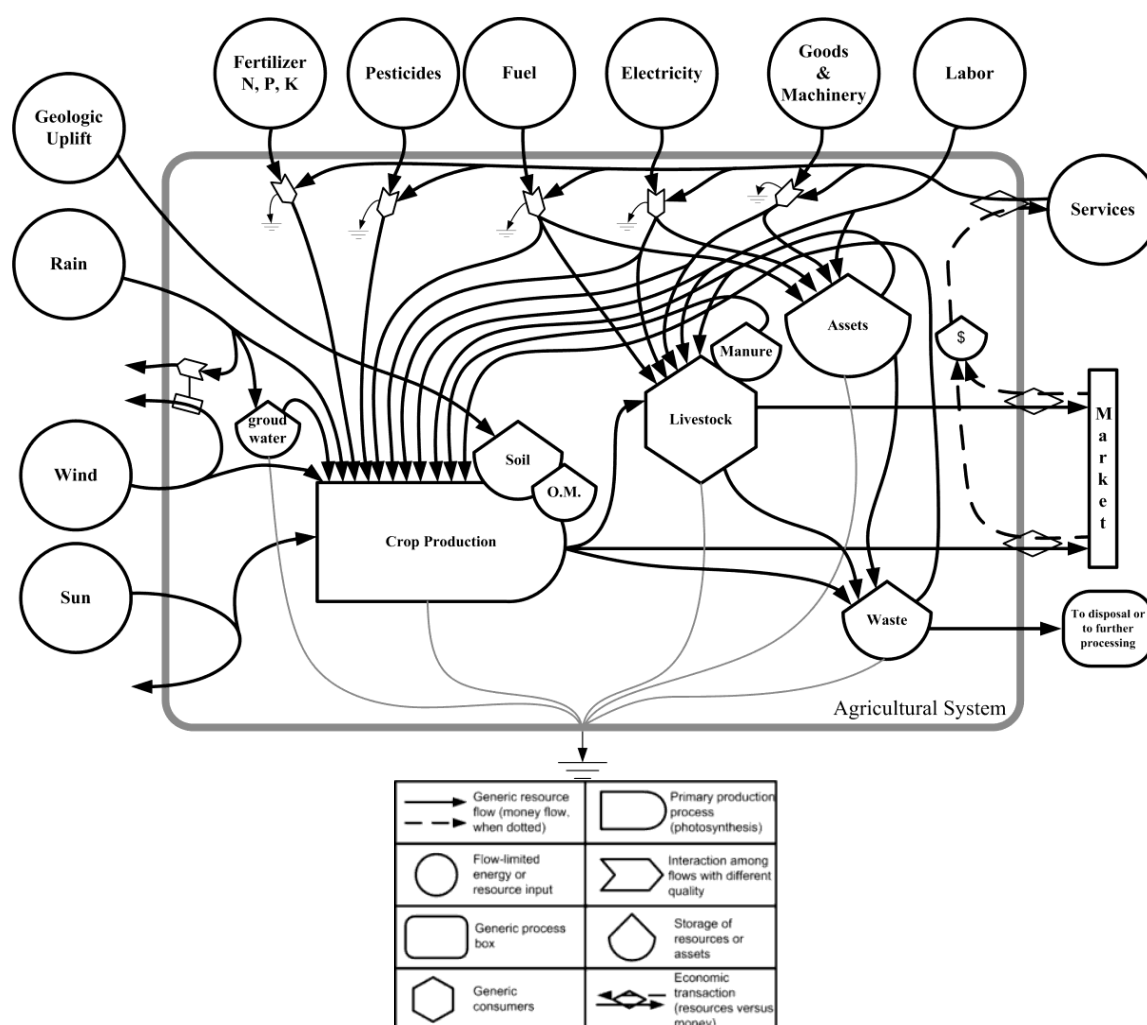


Figure 3. (a) System diagram for the agricultural system in Italy and Campania region. (b) Legend of systems symbols used in Figure 3-a, from Odum, 1996.

1.2.2 Calculation procedure

Based on the systems diagram, tables of the input and output flows were constructed for the two investigated systems (Italian and Scottish agricultures). All data were collected, on a yearly basis, in order to account for the matter, energy and money flows supporting the systems. The livestock sector is not included in the present study due

to lack of data for the Italian system. However, disaggregated data for crop and livestock productions in the Scottish agricultural sector were not available (Viglia *et al.*, 2010). For this reason, in order to calculate energy, material and emissions intensity factors, we decided to proceed according to the rules of Life Cycle Assessment (LCA) (ISO, 2006), by allocating the total input resources according to the economic value of both products. Production costs of agricultural products and livestock were calculated by dividing the allocated amounts of economic investment by the money value of the two typologies of product. Instead, for the emergy synthesis evaluation we applied the emergy algebra (no allocation of input flows), under the assumption that all input flows are needed to generate at the same time the two products, livestock and crops.

3. RESULTS AND DISCUSSION

3.1 Performance of the Italian agricultural sector

Inventory data of the Italian agricultural sector (Zucaro *et al.*, 2010) are converted into cumulative material demand, cumulative energy demand, environmental support, and emissions, in order to generate performance indicators over time. The main calculated indicators are listed in Table 1 as: abiotic material intensity and water intensity (i.e., abiotic matter and water degraded in all the steps of the process); energy intensity (demand of embodied commercial energy); emergy intensity (demand for global environmental support to the process); airborne and waterborne emission intensity (according to selected LCA impact categories). Indicators are calculated in relation to selected functional units (dry mass produced, energy made available in the product; hours of labor invested; hectares of land cropped). Downstream impact per hectare and per hour were also calculated, but are not shown in Table 1. For example, according to Table 1, one euro of GDP generated by the agricultural product required in the year 2006 about 2.4 kg of abiotic matter, 106 m^3 of water, 10.5 MJ of energy (translating into 250 g of oil equivalent), 4.23×10^{12} solar equivalent joules of environmental support, and finally generated a global warming contribution of 760 g of CO_2 -equivalents. These data, and other performance indicators in Table 1 can be used for comparison of the system's performance over time and for comparison with other systems (e.g., the Scottish agriculture).

Table 1. Performance of the Italian agricultural sector in selected years (1985-2006).

	1985	1993	2002	2006
Total Land Cropped (ha)	1.70E+07	1.50E+07	1.45E+07	1.37E+07
Material resource depletion				
MI _{abiot} (g/g d.m.)	0.55	0.61	0.60	0.63
MI _{abiot} (g/€)	3.69E+03	3.02E+03	2.27E+03	2.39E+03
MI _{abiot} (g/J)	3.39E-05	3.77E-05	3.74E-05	3.90E-05
MI _{abiot} (g/ha)	4.02E+06	4.56E+06	4.28E+06	4.43E+06
MI _{abiot} (g/hour)	3.13E+04	3.41E+04	3.31E+04	3.47E+04
MI _{water} (g/g d.m.)	65.56	44.48	36.37	27.92
MI _{water} (g/€)	4.43E+05	2.21E+05	1.37E+05	1.06E+05
MI _{water} (g/J)	4.06E-03	2.75E-03	2.25E-03	1.73E-03
MI _{water} (g/ha)	4.82E+08	3.33E+08	2.57E+08	1.96E+08
MI _{water} (g/hour)	3.76E+06	2.49E+06	1.99E+06	1.54E+06
Total abiotic material requirement	6.83E+13	6.82E+13	6.21E+13	6.07E+13
Total water Footprint	8.19E+15	4.98E+15	3.73E+15	2.69E+15
Energy resource depletion				
GER per unit of mass (J/g d.m.)	2.21E+03	2.63E+03	2.52E+03	2.76E+03
GER per unit currency (J/€)	1.49E+07	1.30E+07	9.47E+06	1.05E+07
GER per unit of energy (J/J)	0.14	0.16	0.16	0.17
GER per ha (J/ha)	1.63E+10	1.97E+10	1.78E+10	1.94E+10
GER per hour of labor (J/hour)	1.27E+08	1.47E+08	1.38E+08	1.52E+08
Oil equiv. (g/g d.m.)	0.05	0.06	0.06	0.07
Oil equiv. (g/€)	3.57E+02	3.11E+02	2.26E+02	2.50E+02
Oil equiv. (g/J)	3.27E-06	3.89E-06	3.72E-06	4.08E-06

Oil equiv. (g/ha)	3.88E+05	4.71E+05	4.26E+05	4.63E+05
Oil equiv. (g/hour)	3.03E+03	3.51E+03	3.29E+03	3.62E+03
EROI (Energy of products/Total embodied energy applied)	7.30	6.15	6.42	5.86
Emergy, demand for environmental support				
Specific emergy (with L&S) (seJ/g d.m.)	3.33E+08	3.67E+08	3.63E+08	3.83E+08
Specific emergy (with L&S) (seJ/€)	4.10E+12	3.64E+12	3.64E+12	4.23E+12
Transformity (with L&S) (seJ/J)	3.75E+04	4.55E+04	5.99E+04	6.90E+04
Empower density (with L&S) (seJ/ha)	4.46E+15	5.50E+15	6.85E+15	7.83E+15
Energy Yield Ratio (with L&S) = U/(F+L+S)	1.14	1.11	1.10	1.08
Environmental Loading Ratio (with L&S) = (N+F+L+S)/(R)	8.40	11.49	12.40	14.39
Climate change				
Global warming (Carbon footprint; CO ₂ -equiv, g/g d.m.)	0.17	0.20	0.18	0.20
Global warming (Carbon footprint; CO ₂ -equiv, g/€)	1.16E+03	9.87E+02	6.92E+02	7.60E+02
Acidification (SO ₂ -equiv, g/g d.m.)	5.82E-04	7.39E-04	1.17E-03	1.22E-03
Acidification (SO ₂ -equiv, g/€)	3.93	3.67	4.40	4.62
Eutrofication (PO ₄ -equiv, g/g d.m.)	6.98E-05	1.01E-04	7.09E-05	7.77E-05
Eutrofication (PO ₄ -equiv, g/€)	4.71E-01	5.02E-01	2.67E-01	2.95E-01

An appropriate selection of indicators from Table 1 is graphically shown in the radar diagram of Figure 4. In order to compare data with different orders of magnitude in the same radar, we applied a normalization procedure (all values are divided by the value of the first year of investigation) in such a way that a larger area suggests a higher relative impact.

Increasing areas in the diagram clearly point out that the Italian agriculture is becoming less sustainable and is day-by-day turning into a fossil fuel based economy. This is affecting its ability to serve as a source of renewable materials, food, energy and ecosystem services (e.g. water holding ability and stabilization of organic matter in soil). The decreasing performance is affected by a mix of factors: large rainfall oscillations and related variation of irrigation practices, decreased amount of arable land cropped, variation of the mix of crops, change in technology (increased agricultural machinery), decrease of labor, increased use of fertilizers and other chemicals. Such variations of input values translate into important changes of the performance indicators, that in turn globally translate into a different shape and area of the radar diagrams.

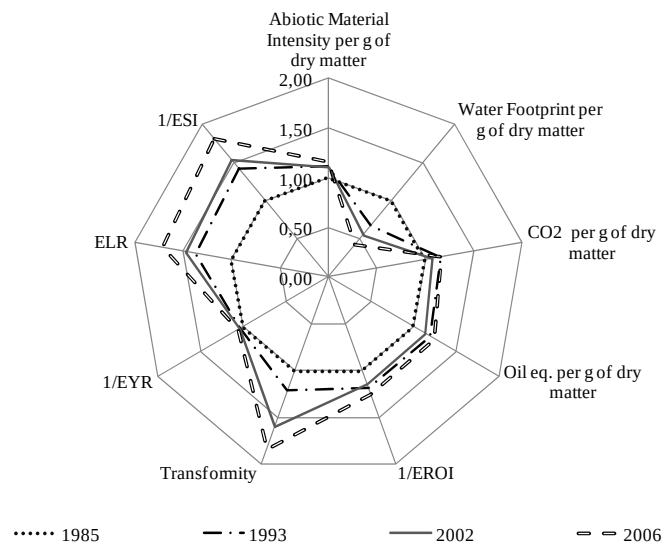


Figure 4. The radar diagram shows the performance indicators of Italian agriculture over time. Values normalised from Table 1.

3.2 Performance of the Scottish agricultural sector

The inventory data of the Scottish agricultural sector (Viglia *et al.*, 2010) show that the direct labor applied, in terms of hours, decreases over time but becomes more

expensive; at the same time, the use of agricultural machinery increases, but it is accompanied by a simultaneous decrease of electricity and fuel use, suggesting higher efficiency in machinery use. Fertilizers decrease from 1991 to 2007 having a peak in the year 2001, while pesticides and herbicides decline steadily. On the product side, the economic value grows in current price terms, while the total dry mass produced is more or less stable and so does the energy content. Tables 2 lists the main indicators obtained by the application of the SUMMA framework to the Scottish agriculture in the years 1991, 2001 and 2007.

Table 2. Performance of the Scottish agricultural sector in selected years (1991-2007).

	1991	2001	2007
Total Land Cropped (ha)	3.92E+06	3.92E+06	4.15E+06
Material resource depletion			
MI _{abiot} (g/g d.m.)	1.57	2.06	1.87
MI _{abiot} (g/€)	1.90E+04	1.50E+04	9.74E+03
MI _{abiot} (g/J)	1.21E-04	1.57E-04	1.43E-04
MI _{abiot} (g/ha)	1.15E+06	1.50E+06	1.32E+06
MI _{abiot} (g/hour)	4.91E+04	6.42E+04	6.46E+04
MI _{water} (g/g d.m.)	4.17E-04	5.14E-04	4.02E-04
MI _{water} (g/€)	6.57E+04	4.93E+04	2.75E+04
MI _{water} (g/J)	4.17E-04	5.14E-04	4.02E-04
MI _{water} (g/ha)	3.96E+06	4.92E+06	3.71E+06
MI _{water} (g/hour)	1.69E+05	2.10E+05	1.82E+05
Total abiotic material requirement	4.49E+12	5.88E+12	5.46E+12
Total water Footprint	1.55E+13	1.93E+13	1.54E+13
Energy resource depletion			
GER per unit of mass (J/g d.m.)	3.95E+03	4.99E+03	4.35E+03
GER per unit currency (J/€)	4.77E+07	3.64E+07	2.26E+07
GER per unit of energy (J/J)	0.30	0.38	0.33
GER per ha (J/ha)	2.88E+09	3.63E+09	3.06E+09
GER per hour of labor (J/hour)	1.23E+08	1.55E+08	1.50E+08
Oil equiv. (g/g d.m.)	0.09	0.12	0.10
Oil equiv. (g/€)	1.14E+03	8.69E+02	5.41E+02
Oil equiv. (g/J)	2.15E-06	2.11E-06	1.63E-06
Oil equiv. (g/ha)	6.87E+04	4.99E+03	7.31E+04
Oil equiv. (g/hour)	2.94E+03	3.79E-01	3.59E+03
EROI (Energy of products/Total embodied energy applied)	3.30	2.64	3.01
Energy, demand for environmental support			
Specific energy (with L&S) (seJ/g d.m.)	5.79E+09	6.31E+09	6.00E+09
Specific energy (with L&S) (seJ/€)	2.75E+13	2.15E+13	1.64E+13
Transformity (with L&S) (seJ/J)	4.45E+05	4.80E+05	4.58E+05
Empower density (with L&S) (seJ/ha)	4.22E+15	4.59E+15	4.23E+15
Emergy Yield Ratio (with L&S) = U/(F+L+S)	1.40	1.33	1.42
Environmental Loading Ratio (with L&S) = (N+F+L+S)/(R)	4.00	4.83	3.75
Climate change			
Global warming (Carbon footprint; CO ₂ -equiv, g/g d.m.)	0.34	0.43	0.40
Global warming (Carbon footprint; CO ₂ -equiv, g/€)	5.77E+02	6.24E+02	5.23E+02
Acidification (SO ₂ -equiv, g/g d.m.)	1.73E-03	2.28E-03	1.90E-03
Acidification (SO ₂ -equiv, g/€)	2.95	3.34	2.49
Eutrofication (PO ₄ -equiv, g/g d.m.)	1.11E-04	1.39E-04	1.23E-04
Eutrofication (PO ₄ -equiv, g/€)	0.19	0.20	0.16

A graphical overview of results is provided in Figure 4, where a better performance is shown by the Scottish system in the year 2007 compared to the previous years, apparently indicating an improvement of the system's performance. It should be noted that the radar diagram was generated by only using intensive indicators, not extensive ones, so that the diagram's behaviour is not dependent on the different total area of the system in the investigated years.

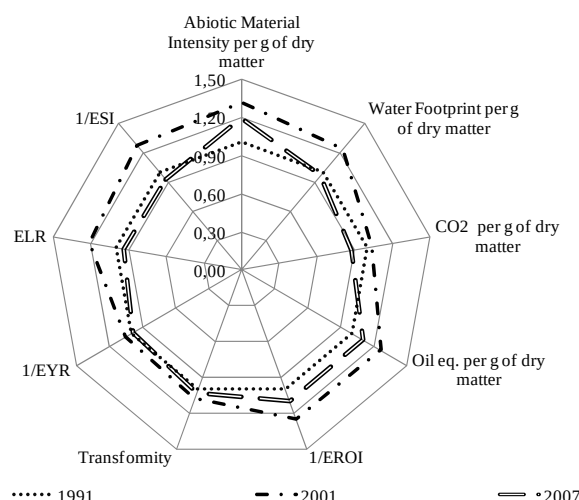


Figure 4. The radar diagram shows the performance indicators of Italian agriculture over time. Values normalised divided by the value of the first year of investigation from Table 2.

3.3 Comparison of the Italian and Scottish agricultural sectors

The possibility to compare selected impact categories of the investigated systems (e.g. energy depletion, contribution to global warming, demand of environmental support, acidification) is an important aspect of the SUMMA approach. Much more important is that the SUMMA calculation procedure allows to identify what are the categories that are responsible of the largest impacts and, within each category, what is the process step that generates the highest loading. The analyst can therefore design and test change scenarios based on “what if” experiments and sensitivity analysis procedures.

The radar diagram (Figure 5) compares selected performance indicators for the two countries. The analytical inventory tables, not shown in this paper show for Italy (Zucaro *et al.*, 2010) decreased land cropped, slightly decreasing dry mass yield and yield per ha, slightly decreasing of total chemical fertilizers use and use per ha, increased use of machinery and fuel, and decreased use of water; instead the Scottish agriculture (Viglia *et al.*, 2010) shows relatively stable land cropped, stable dry matter yield, decreased use of fertilizers, constant use of water and finally increased use of machinery coupled to constant use of fuels.

The joint use of analytical Tables, and Indicators Tables (Table 1, Table 2) allows a comprehensive understanding of the dynamics of the two systems over time as well as a deep insight into the different aspects (mass, energy, income, labor and land related), in order to identify and highlight the need for improvement strategies.

Figure 5 suggests that the agriculture of Italy is more environmental impacting than the Scottish agriculture. It shows a much higher water footprint and a higher energy demand per ha in Italy. When indicators are calculated on “per gram” basis, costs and impacts are hidden, because of the Italian higher productivity per hectare. The better production performance of Italy (higher yield per ha, higher total yield) has an environmental cost that can be clearly identified in the indicators of Tables 1 and 2, and also clearly appears in the aggregated emergy indicators of Figure 5 (lower Emergy Yield Ratio, higher Environmental Loading Ratio and lower Emergy Sustainability Indicator). The Energy Return on (Energy) Investment (EROI) is much higher for Italy than for Scotland (Figure 6), in spite of the higher energy intensity per ha, suggesting that better climate conditions and land fertility still allow a growing marginal return, compared to Scotland.

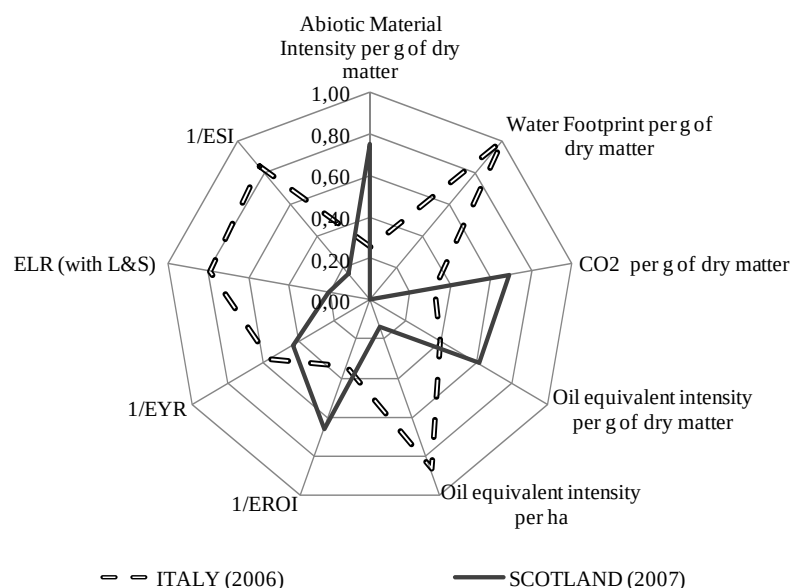


Figure 5. Radar diagram showing the comparison of the performance indicators of agriculture in Italy and Scotland. Values normalised with reference to the total impact generated (the total impact is calculated by adding the values of the two systems, then, in order to calculate its fraction or percentage, the value of the indicator is divided by the sum of the two) from Tables 1 and 2.

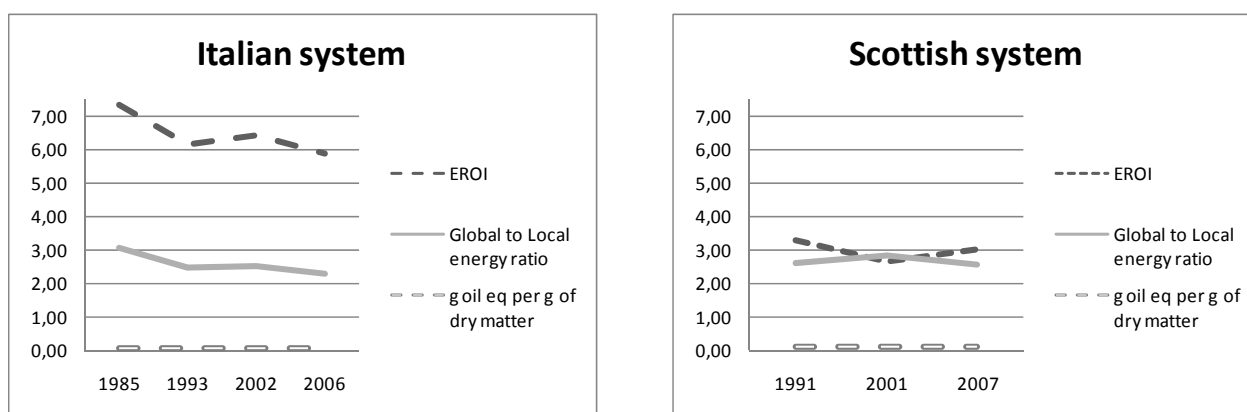


Figure 6. Energy based indicators of the agricultural sector in Italy and in Scotland over time.

Figure 6 shows another important indicator, namely the Global to Local energy ratio. Its value close to 3 means that each joule of energy used locally (directly in the farm) costs more or less 3 joules invested directly or indirectly in the process. A change in the amount or in the mix of direct energy and resources used affects the global scale, since it depends on the metabolic chain that is followed to deliver the input resources and since there is energy embodied in goods, materials and infrastructures. For example using steel locally involves the whole chain that provides such a steel, from mining of iron ore to the refining of the product. Therefore, if more or less steel is used, or if steel is replaced by aluminum, or if recycling patterns are implemented, this will translate into a bigger or smaller burden placed on the larger scale. Global-to-local use ratios can be calculated for almost all impact categories (matter demand, water demand, impact of emissions) but for energy, that is by definition focused on the global scale only. Providing a clear assessment of such aspects is important for policy. The global-to-local ratios may change due to a multiplicity of factors (efficiency of the productive chain, mix of supply, etc) and it is possible to affect these factors through improvement strategies.

In conclusion, it clearly appears that both investigated systems generate not only local but also and mainly global impacts in the surrounding regions where primary input

are processed. This means that an improvement of the local performance leads to a major positive effect on the regional and global scale. The SUMMA approach is therefore designed in such a way that allows “scenario making” experiments, based on selectively assuming technical changes or better use of the most crucial production factors in order to ascertain how these changes affect the final performance indicators.

4. CONCLUSION

The study shows that analytical inventory procedures, joint use of different evaluation methods characterised by different spatial and time-scales, comparison of intensive and extensive indicators over time and finally scenario-making experiments based on sensitivity analysis methods provide a powerful tool for comprehensive understanding and policy-making.

The two investigated case studies (Italian and Scottish agricultures) underlined a very different dynamics. The Italian agricultural system seems increasingly becoming less sustainable, because of its heavy dependence on fossil fuels. The Scottish system shows instead a better global performance. A problem suggested by the assessment is that the best performing system is not also the one characterised by the highest productivity. Such an aspect must be taken into account by policy makers, in that it affects the ability of the system to supply food, energy and materials to meet the growing needs of local populations.

ACKNOWLEDGEMENTS

The Authors gratefully acknowledge the financial support received from the European Commission within the 7th Framework Program, Project no.217213, SMILE - Synergies in Multi-scale Inter-Linkages of Eco-social systems. Socioeconomic Sciences and Humanities (SSH) Collaborative Project FP7-SSH-2007-1.

REFERENCES

- Bargigli, S., Raugeri, M. and Ulgiati, S., 2005. “Mass flow analysis and mass-based indicators”. In: *Handbook of Ecological Indicators for Assessment of Ecosystem Health*. Sven E. Jorgensen, Robert Costanza, and Fu-Liu Xu Editors. Pp. 353-378. CRC Press, 2005.
- Biondi, P., Panaro, V., Pellizzi, G., 1989. *Le Richieste di Energia del Sistema Agricolo Italiano*. CNR, Consiglio Nazionale delle Ricerche, Progetto Finalizzato Energetica, Sottoprogetto Biomasse ed Agricoltura, Report LB-20, Roma, Italia.
- Brown, M.T. and Ulgiati, S., 2004. *Emergy Analysis and Environmental Accounting*. In: *Encyclopedia of Energy*, C. Cleveland Editor, Academic Press, Elsevier, Oxford, UK, 2004, pp. 329-354.
- CORINAIR, 2007. *EMEP/CORINAIR Emission Inventory Guidebook – 2007*; <http://www.eea.europa.eu/publications/EMEPCORINAIR5/>
- Herendeen, R., 1998. “Embodied energy, embodied everything: now what?” In: *Proceedings of the First International Workshop Advances in Energy Studies. Energy Flows in Ecology and Economy*, 13-48/642, MUSIS, Roma, Italy.
- Hinterberger, F. and Stiller, H., 1998. “Energy and Material Flows”. In: *Advances in Energy Studies. Energy Flows in Ecology and Economy*. Ulgiati S., Brown M.T., Giampietro M., Herendeen R.A., and Mayumi K. (Eds). Musis Publisher, Roma, Italy; pp.275-286.
- ISO, 14040, 2006. *Environmental management - Life cycle assessment - Principles and framework*. International Standard Organization, June 2006, Brussels. www.iso.org
- ISO, 14044, 2006. *Environmental management - Life cycle assessment - Requirements and guidelines*. International Standard Organization, June 2006, Brussels. www.iso.org.
- ISTAT, 2006. *National institute of statistics*, www.istat.it.

- Leiden, 2000. *CML2 baseline 2000* (Centre of Environmental Science, Leiden University, NL, 2000), http://www.pre.nl/simapro/impact_assessment_methods.htm.
- Odum, H.T., 2000. *Handbook of Emergy Evaluation Folio 2: Emergy of Global Processes*. Centre for Environmental Policy, University of Florida, Gainesville
- Odum, H.T., 1996. *Environmental Accounting: Emergy and Environmental Decision Making*. John Wiley and Sons. New York, 370 pp.
- Schmidt-Bleek, F., 1993. "MIPS re-visited". *Fresenius Environ. Bull.* 2, 407–412.
- Ulgiati, S., Ascione, M., Bargigli, S., Cherubini, F., Federici, M., Franzese, P.P., Raugei, M., Viglia, S., and Zucaro, A. 2010. "Multi-method and multi-scale analysis of energy and resource conversion and use". In: *Energy Options Impact on Regional Security*. NATO Science for Peace and Security Series – C: Environmental Security. Frano Barbir and Sergio Ulgiati, Editors. Springer, Netherlands. Pp.1-36.
- Ulgiati, S., Raugei, M. and Bargigli, S., 2006. "Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment". *Ecological Modelling*, 190: 432–442.
- Viglia, S., Zucaro, A., Franzese, P. P., Blackstock, K. L., Matthews, K. B. and Ulgiati, S., 2010. "Exploring resource use and biophysical constraints of Scottish agriculture at regional and national scales". In: *Proceedings of Sixth Biennial Emergy Research Conference*. Submitted.
- Zucaro, A., Viglia, S. and Ulgiati, S., 2010. "Emergy evaluation of Italian agriculture across space and time scales". In: *Proceedings of Sixth Biennial Emergy Research Conference*. Submitted.

ENERGY, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF NON-FOOD USE OF *BRASSICA CARINATA*

S. Fahd^{*1}, G. Fiorentino¹, S. Mellino¹, G. Rótolo² and S. Ulgiati¹

¹ Department of Sciences for the Environment, Parthenope University, Napoli,
Italy

² National Institute of Agricultural Technology (INTA), Oliveros Agriculture
Experimental Station, Argentina

ABSTRACT

The perspective of this study is to identify non-food crops that fit the Mediterranean basin region and assess the economic, energetic and environmental feasibility of their conversion into bioenergy and biochemicals. Large research efforts are being displayed for evaluating the potential use of non-food crops for production of energy, textiles, health and beauty products, pharmaceuticals, packaging and other industrial applications. The implementation of biomass-based agro-industrial systems (biorefineries) is believed to contribute to maintaining employment and creating new jobs in rural areas, avoiding land abandonment and further urbanization.

The focus of our attention was on the possible employment of marginal lands degraded by previous uses. In particular, *Brassica carinata*, a non-food crop, was selected for Southern Italy. In an earlier study, we found that the net energetic gain of converting both Brassica seeds and residues to energy use was small and not sustainable from the economic viewpoint. Therefore, the biorefinery concept was considered as a hypothesis to be further explored in order to provide innovative use of marginal land and additional income to farmers. The results obtained are promising, although further studies are needed for full assessment of the environmental impact and energy cost of production.

Keywords: biorefinery, energy accounting, non-food crops, *Brassica carinata*

1. INTRODUCTION

The promotion of non-food crops on marginal lands has started one decade ago, in order to prevent competition for arable land in food production. Many specialty crops have already been investigated for their production capacity of non-food oils or high lignocellulosic biomass yield. The choice of specialty oil crops for further development depends on different geographical locations and potential use of products and by-products. In this context, it was suggested that the development of non-food crops is important on set-aside land or marginal land. Our selection of land use is based on the integration of GIS data (spatially continuous) with data derived from the agricultural census (spatially discrete).

We designed two cropping processes in two equal portions of marginal land, one to be dedicated to cropping for energy and one to support a biorefinery project. In Fahd et al., 2010, we assessed the feasibility of cropping for energy in marginal land of the Campania region, selecting land polluted by previous uses (industrial or landfill use). Due to the pollution of land, no uses were possible other than energy use (combustion). Results demonstrated that although an energy return was in principle possible in the ratio of about 2:1, the whole process was unfeasible from the economic point of view, investment costs being four times higher than saved oil value (due to the low market price of oil). The economic costs of the agricultural phase are dominating, accounting for more than 90% of the total investment (Fahd et al., 2010). This indicates that the search for any

* Corresponding author; E-mail: sandra.fahd@uniparthenope.it

economic improvement of energy cropping must address the agricultural step, the others being almost negligible. When all factors are accounted together, the option of cropping for energy on marginal land becomes much less attractive than claimed by some.

The aim of this study is to evaluate a different scenario for energy and biochemicals production in a biorefinery framework from dedicated crops, still in Campania region. The only difference is the choice of land, that is now identified as marginal, but not polluted, so that the chemicals extracted can be used without risk for human health. The challenge is to prove the feasibility of an agro-industrial activity capable to generate economic, energy, and environmental advantages from a multiple use of the photosynthetic process. An added value may be found in exploiting the information content of biopolymers and biochemicals, instead of just burning them as no value substrates. In addition to the potential economic value of such products, their replacement energy value is also worth being explored.

1.1 The biorefinery concept

Biomass and, in particular, plant-based raw materials are gaining more and more attention as an alternative option to shrinking fossil reserves, as feedstocks for industrial production, for both the energy and non-energy use, including chemicals and materials (EC, 2004). The term “biorefinery” was established in the 1990s to indicate a system that produces useful products, using a renewable resource like biomass as input, in comparison to petroleum refinery where fossil fuels are used to generate power, fuels and chemicals (Schilling, 1995). Therefore, a biorefinery aims at the optimum exploitation of biomass resources in order to generate final products able to replace energy carriers and material products derived from fossil/non-renewable sources, thus implementing the much needed transition towards a more sustainable society.

2. MATERIALS AND METHODS

2.1 *Brassica carinata*. Products and uses

Plants belonging to the genus *Brassica* are of great economic and nutritional importance and include crops widely used for oil extraction. *Brassica* oil production occupies the fourth position in volume in the world after soybean oil, palm seed oil, and cottonseed oil, and it is the most important oilseed crop in Europe (FAO, 2002). Recently, countries like Spain, Greece, and Italy, with regions characterized by semi-arid climates, are showing interest in the exploitation of *Brassica carinata* for production of biodiesel and solid biomass. This crop represents an interesting source of non-food raw resources either for energy (liquid biofuels from seeds) and high value-added biochemicals from straw and press cakes, perfectly fitting with the biorefinery concept (Figure 1).

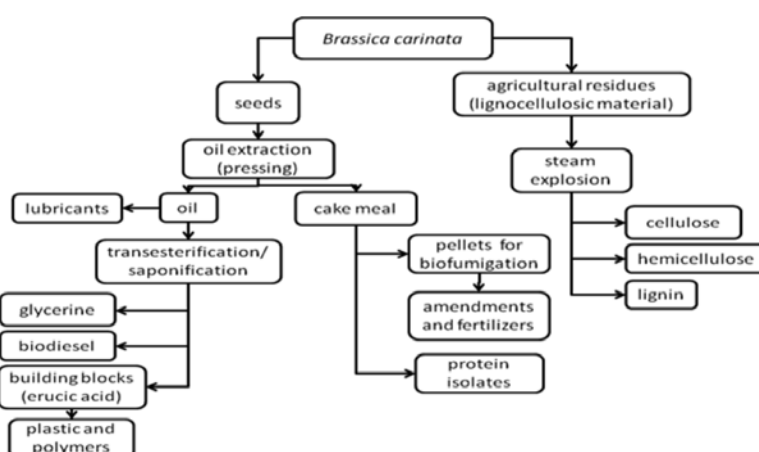


Figure 1. Schematic flow chart of a biorefinery system based on *Brassica carinata*.

2.1.1 Seeds

The oil derived from the defatted seeds of Brassicaceous plants, characterized by a high content in erucic acid, is of no interest for food purposes but has found several applications including the production of biofuels. It can also be applied as a basic material for biolubricants (in tannery industry) or to produce via saponification the erucic acid that represents a building block for organic synthesis and production of plastics and polymers (Lazzeri et al., 2008).

2.1.2 Cake meal

The defatted meal that is left after oil extraction is rich in proteins, although its use for human nutrition presents some problems because it also contains antinutritional components such as glucosinolates and phytates, as well as a high cellulose content. For this reason, the Brassica defatted meal is only used for animal feeding and as an organic fertilizer. Protein isolates (PI) are frequently prepared from defatted meals by solubilization of proteins in alkaline media and precipitation at the isoelectric point. This protocol allows for separation of proteins from non-protein components such as sugars, fiber and antinutritional chemicals. High temperatures and organic solvents used during the process of oil extraction may cause denaturation of proteins, reducing protein solubility and extraction yields and consequently impairing other functional properties.

Proteins represent the main component of defatted meal (38.9%). The amino acid composition of the proteins of *B. carinata* meal is balanced in all essential amino acids. Fiber is the second most abundant component in *B. carinata* defatted meal, with a value of 31.8%. The presence of glucosinolates is one of the main characteristics of Brassicaceae. In the defatted meal glucosinolates represent 5.1%. Glucosinolates and the products that are released after their hydrolysis are considered antinutritional factors, since they reduce the availability of iodine. As glucosinolates, phytic acid (3.1% of the defatted meal) has been traditionally considered an antinutritional factor by decreasing the availability and adsorption of minerals. Among minor components, noticeable is the presence of polyphenols (0.3%), considered antinutritional factors as well, but with attractive antioxidant properties.

2.1.3 Agricultural Residues

Herbaceous agricultural residues represent a major source of lignocellulosic material with considerable potential for use in biomass-to-ethanol renewable energy schemes (Ballesteros et al., 2002). Lignocellulose materials consist of three primary chemical fractions or precursors: (a) hemicellulose/polyoses, sugar polymer of predominantly pentoses, (b) cellulose, a glucose polymer and (c) lignin, a polymer of phenols. In particular, furfural and hydroxymethylfurfural are interesting products. Furfural is the starting material for the production of Nylon 6,6 and Nylon 6. Lignin can generate fuel, adhesives or binders. About 21% of *B. carinata* dry matter consists of substances that can be extracted by means of organic solvents and water. Cellulose and lignin content (32.7 and 18.7%, respectively) are in the range reported for lignocellulosic biomass of food crops, whilst the hemicellulose fraction (hemicellulosic-derived sugars are xylose/arabinose/mannose/galactose) comprises 21.9% of raw material, xylose being the main sugar component (82%).

2.2 The assessment method

The biodiesel is obtained as oil from the crushing of the seeds and then refined through a transesterification process in order to render it more compatible with combustion in a diesel engine. The main process is therefore based on three main phases starting with the agricultural production and ending up with chemical conversion to biodiesel. The transport of seeds to the biodiesel plant for processing was also included in the assessment, as an intermediate step.

The process evaluation focused on the main four steps (agricultural production, transport of seeds to the conversion plant, oil extraction and finally biodiesel production (transmetilesterification). Each step was investigated under a multiplicity of points of view, within a multi-method framework named SUMMA (SUstainability Multi-scale Multi-method Assessment; Ulgiati et al., 2006), jointly based on assessing material demand (Schmidt-Bleek, 1993; Hinterberger and Stiller, 1998; Ritthoff et al., 2003; Bargigli et al., 2005), embodied energy (Slesser, 1974; Herendeen, 1998; Cleveland and Costanza, 2008), emergy (a measure of environmental support; Odum, 1988, 1996; Ulgiati et al., 1995; Brown and Ulgiati, 1999; Brown and Ulgiati, 2004) and emission flows (CORINAIR, 2007; US-EPA, 2010; Leiden, 2000). In so doing, a comprehensive evaluation of each step and final results is achieved at local and global scales. Here we only show the calculation procedure used for the embodied energy evaluation (Table 1 and Table 2).

2.2.1 The embodied energy method.

The commercial energy invested into the whole chain of processes that lead from extraction and processing of raw materials and resources to the final product(s) via crop production, harvesting, transport and conversion is calculated by firstly performing an inventory of all input energy and matter flows to the agricultural and industrial processes. Input flows are then multiplied by suitable conversion coefficients which express the unit energy demand “embodied” in each flow. Such coefficients are available in published embodied energy and Life Cycle Assessment literature. The embodied energy assigned to each input flow (i.e. the commercial energy used up to make that flow) is calculated according to the following equation: $E = \sum_{i=1}^n f_i \times c_i$

Equation (1)

where:

E = embodied energy

f_i = i-th input flow of matter or energy

c_i = embodied energy coefficient of the i-th flow (from literature or calculated in this work).

In this study, each input flow is multiplied by a suitable oil equivalent intensity (amount of conventional commercial oil required to generate one unit of product), to yield the total oil equivalent demand and its heat content. Oil equivalent is converted to heat units by multiplying by 41860 J/g_{oil}. Summing up the embodied energy values of all input flows in all process steps we calculated the total energy invested into the process, i.e. the total energy cost of the product through energy cropping. The method focuses on fuels and electricity, fertilizers and other chemicals, machinery, and assets supplied to the process in terms of the oil equivalent energy required to produce them, expressed in energy units per physical unit of good or service delivered (for instance, MJ per kg of steel). The method is concerned with the depletion of fossil energy, and therefore all process inputs of material and energy that do not require the use of fossil and fossil equivalent resources are not accounted for.

3 RESULTS

Table 1 shows the calculation procedures concerning the embodied energy of Brassica carinata production and conversion while Table 2 deals with the industrial phase. Tables yield the energy intensities (energy invested per unit of product) of intermediate and final products. In the presence of more than one product (straw and seeds; oil and press cake; etc.) input flows are allocated to the product according to their percentage energy content.

Table 1. Energy flows in the Agricultural and Transport phase.

Description of flow	Unit	Raw Amount ($\text{ha}^{-1} \text{yr}^{-1}$)	Energy Intensity Factor (g oil eq. unit^{-1})	Ref.	Oil Eq. Demand (g oil eq. $\text{ha}^{-1} \text{yr}^{-1}$)	Energy Demand ($\text{J ha}^{-1} \text{yr}^{-1}$)
Agricultural phase						
Imported Input						
Diesel and heavy fuel	g	7.74E+04	1.23	[a]	8.48E+04	3.55E+09
Additional Energy (heavy fuel oil) for diesel refining	g	1.61E+04	1.23		1.64E+04	6.88E+08
Fertilizers						
Nitrogen (N)	g	5.41E+04	1.75	[a]	9.48E+04	3.97E+09
Phosphate (PO ₄)	g	2.00E+04	0.32	[a]	6.40E+03	2.68E+08
Agricultural Machinery						
<i>steel and iron</i>	g	3.15E+02	0.91	[b]	2.86E+02	1.20E+07
<i>aluminium</i>	g	5.37E+01	5.36	[b]	2.88E+02	1.20E+07
<i>rubber and plastic material</i>	g	3.84E+00	3.00	[a]	1.15E+01	4.82E+05
<i>fraction of copper</i>	g	1.15E+01	2.21	[c]	2.54E+01	1.06E+06
Seeds	g	8.00E+03			5.86E+02	2.45E+07
Total Energy Demand					2.04E+05	8.52E+09
Products and by-products (with allocation according to energy content)						
Seeds produced - dry matter	g	1.20E+06	0.07	[d]		
Straw (d.m., 30% left in soil)	g	2.38E+06	0.05	[d]		
Transportation Phase						
Seeds produced	g	1.20E+06	0.07	[d]	8.80E+04	3.68E+09
Steel for transport machinery	g	4.32E+02	1.91	[a]	8.25E+02	3.45E+07
Diesel for transport	g	9.00E+02	1.23	[a]	1.11E+03	4.64E+07
Total Energy Demand					8.99E+04	3.76E+09
Products transported to the gate of the plant						
Seeds delivered	g	1.20E+06	0.07			
[a]: Biondi <i>et al.</i> , 1989; [b]: Bargigli, 2002; [c]: Our calculation from energy intensity data; [d]: Our calculation performed in this study.						

Results highlight the following preliminary aspects:

a) Energy costs increase with manufacturing. All indicators increase with further processing steps, including those for co-products, due to the allocated contribution from previous steps. It must be noted that, since allocation of inputs was made according to the energy content in each co-product, the performance indicators *per unit of energy delivered* are the same for the co-products of each step, while the indicators *per unit of mass delivered* (shown in the Tables) and *unit economic value generated* are always different.

b) Energy demand: It takes only 0.07 g oil equivalent to make one g of seeds. The requirement is much higher for Brassica oil (0.29 g oil equiv) and for biodiesel (0.51 g). The final results is that half a gram of oil is invested to generate 1 g of oil equivalent energy. This means that the net energy delivered to society is only 50% of the total yield and that two hectares are needed in order to make one "net hectare".

Table 2. Energy flows for Industrial Phase.

Description of flow	Unit	Raw Amount ($\text{ha}^{-1} \text{yr}^{-1}$)	Energy Intensity Factor (g oil eq. unit^{-1})	Ref.	Oil Eq. Demand (g oil eq. $\text{ha}^{-1} \text{yr}^{-1}$)	Energy Demand ($\text{J ha}^{-1} \text{yr}^{-1}$)
Brassica oil extraction and refining phase						
Seeds delivered	g	1.20E+06	0.07	[d]	8.99E+04	3.76E+09
Electricity	J	1.04E+09	9.95E-05	[e]	6.24E+04	2.61E+09
Natural gas	g	3.64E+04	1.66	[f]	4.34E+04	1.82E+09
Additional energy for natural gas refining	g	5.20E+03	1.66	[f]	6.20E+03	2.59E+08

Hexane	g	3.41E+03	1.32	[g]	4.50E+03	1.88E+08
Infrastructure						
<i>Stainless steel</i>	g	1.45E+02	1.91	[a]	2.77E+02	1.16E+07
<i>Steel</i>	g	2.77E+02	1.91	[a]	5.29E+02	2.22E+07
<i>Cement</i>	g	7.39E+02	0.11	[a]	8.13E+01	3.40E+06
Total Energy Demand					2.07E+05	8.68E+09
Products and by-products (with allocation according to energy content)						
Brassica oil	g	3.96E+05	0.29	[d]		
Brassica meal or pellets	g	6.96E+05	0.13	[d]		
Transesterification biodiesel production						
Brassica oil	g	3.96E+05	0.29	[d]	1.16E+05	4.85E+09
Electricity	J	1.79E+08	9.95E-05	[e]	1.07E+04	4.47E+08
Natural gas	g	1.36E+04	1.66	[f]	1.62E+04	6.77E+08
Additional energy for natural gas refining	g	1.94E+03	1.66	[f]	2.31E+03	9.67E+07
Methanol	g	5.66E+04	1.03	[h]	5.82E+04	2.44E+09
Acid (hydrochloric acid)	g	1.19E+04	n.a.		0.00E+00	0.00E+00
Catalyst (sodium hydroxide NaOH)	g	8.73E+03	n.a.		0.00E+00	0.00E+00
Infrastructure						
<i>Iron</i>	g	5.46E+00	0.91	[b]	4.97E+00	2.08E+05
<i>Steel</i>	g	9.11E+02	1.91	[a]	1.74E+03	7.28E+07
<i>Cement</i>	g	2.64E+02	0.11	[a]	7.25E+02	3.04E+07
Water	g	3.11E+05	1.31E-04	[i]	4.09E+01	1.71E+06
Total Energy Demand					2.06E+05	8.61E+09
Products and by-products (with allocation according to energy content)						
Biodiesel	g	3.88E+05	0.51	[d]		
Glycerin	g	3.88E+04	0.22	[d]		
[a]: Biondi <i>et al.</i> , 1989; [b]: Bargigli, 2002; [c]: Our calculation from energy intensity data; [d]: Our calculation performed in this study; [e]: Our calculation from Boustead and Hancock, 1979; [f]: Boustead and Hancock, 1979; [g]: Value equal to Gasoline from Biondi <i>et al.</i> , 1989; [h]: Boustead and Hancock, 1979; [i]: Our calculation from energy costs of common materials						

The energy costs of production of seeds, straw, seed oil, press cake, biodiesel, and glycerin are the starting points for a more complete evaluation of the final biorefinery products. Further energy is invested to extract value-added chemicals out of straw and press-cake in a next industrial step. Such evaluation is still in progress.

4 RESULTS AND DISCUSSION FOR A BIOREFINERY SCENARIO

The land allocated to agricultural purpose in Campania region has been steadily decreasing over years (ISTAT, 2006). If we subtract from the land available in 1985, the still available agricultural land in 2006 together with the polluted land and the urbanised areas, we reach a figure of 155,000 ha missing within the statistics. These lands are no more accounted for as agricultural production sites. They are very likely land abandoned because they do not provide enough income to the owner.

Assuming that we can crop *Brassica carinata* in part of the missing marginal lands (43183 ha) of the region and that all the products (biodiesel) and co-products (straw and press cake) are used respectively for energy and as a source of biochemicals and biomaterials, we can calculate if these products are potentially capable to provide a suitable income to the farmer. The amount of hectares indicated was purposefully chosen in order to compare with the results of cropping a similar amount of marginal land for energy purpose in Fahd *et al.*, 2010. Yield, energy and economic costs can be considered the same in the two designs, while the value of the output (only energy in the previous study or energy + biorefinery products in the present study) is different and depends on the market value of biochemicals and polymers as well as on their energy replacement value.

In Table 3 we show data about (a) the percentage of material that can be extracted from each specific by-product, (b) the total amount of products that can theoretically be

obtained per ha cropped with Brassica in Campania Region, and (c) the total mass of each product obtained by cropping the same number of hectares used in the companion study (Fahd et al., 2010).

A large amount of biomass is available and only four products are significant from the point of view of mass and economic value:

- Biodiesel, which is the main product from the seeds;
- Proteins, major constituents of the cake meal;
- Glucose, from the cellulosic fraction of the agricultural residues;
- Xylose, from the hemicelluloses fraction of the agricultural residues.

Other products are also available, e.g. lignin, the market value of which is smaller or not yet defined. However, all of them may be part of a global biorefinery design. The total value of biorefinery products would be roughly 150 million euro. Since production and extraction have a non-negligible cost, the latter must be subtracted from the total value of products, in order to ascertain the real economic feasibility.

The total cost for the production and of seeds, straw, biodiesel and cake meal can be obtained from Fahd et al. (2010), where an equivalent amount of marginal land is assumed to be cropped with Brassica for energy purpose.

Table 3. Bio-products from marginal land in Campania Region.

Products and by-products	Percentage of extraction	Mass of product (kg ha ⁻¹ yr ⁻¹)	Total mass from 43183 ha of Brassica (kg yr ⁻¹)	Market Price (€ kg ⁻¹)	Reference for price	Total value (€)
Seeds (from Brassica)		1200.00	5.18E+07			
Oil (from seeds)	33.0%	396.00	1.71E+07			
Lubricants (*)	6.0%	23.76	1.03E+06	0.88	[a]	9.03E+05
Biodiesel (*)	98.0%	388.08	1.68E+07	0.78	[a]	1.31E+07
Glycerin (10 % from biodiesel)	10.0%	38.81	1.68E+06	0.11	[a]	1.76E+05
Erucic Acid (*)	n.a.	n.a.	n.a.	n.a.		
Plastics & polymers (from erucic acid)	n.a.	n.a.	n.a.	n.a.		
Cake Meal (from seeds)	58.0%	696.00	3.01E+07			
Proteins (^)	39.0%	271.44	1.17E+07	1.60	[b]	1.88E+07
Fibers (^)	31.8%	221.33	9.56E+06	0.11	[c]	1.05E+06
Glucosinates (^)	5.1%	35.50	1.53E+06			0.00E+00
Soluble sugar (^)	5.7%	39.67	1.71E+06	2.40	[b]	4.11E+06
Others materials (^)	18.4%	128.06	5.53E+06			
Agricultural residues (from Brassica)		3400.00	1.47E+08			
Cellulose (°)						
Glucose	32.5%	1105.00	4.77E+07	0.30	[d]	1.43E+07
Hemicellulose (°)						
Xylose	18.0%	612.00	2.64E+07	3.50	[e]	9.25E+07
Galactose	1.5%	51.00	2.20E+06	n.a.		
Arabinose	1.2%	40.80	1.76E+06	n.a.		
Mannose	1.2%	40.80	1.76E+06	n.a.		

Lignin (°)	18.7%	635.80	2.75E+07	0.20	[f]	5.49E+06
Others materials (°)						
Ash	5.2%	176.80	7.63E+06			
Extractives	20.9%	710.60	3.07E+07			
Total economic income from biorefinery chain						1.50E+08
(*) from oil; (^) from cake meal; (°) from agricultural residues [a] www.icipricing.com ; [b] Average value Kamm <i>et al.</i> , 2008; [c] Our calculation from Houtman, 1997; [d] Kamm <i>et al.</i> , 2008; [e] Murthy <i>et al.</i> , 2005; [f] www.bioeconomyconference.org						

Table 4. Economic balance between the total economic investment for biorefinery chain and total production income.

Total economic investment for energy purpose €/yr	2.87E+07
Cost for biorefinery plant €/yr	4.26E+07
Total cost (a) €/yr	7.13E+07
Economic income from biorefinery chain (b) €/yr	1.50E+08
Net economic (b-a) €/yr	7.90E+07
Ratio b/a	2.11

5 CONCLUSIONS

Brassica carinata (and other crops with similar or better characteristics in terms of yield and cultural practices required) is suitable to be used in a biorefinery production chain. Generating energy alone is not an economically profitable production pattern, although we demonstrated (Fahd *et al.* 2010) that the output/input energy ratio is close to 2:1. All by-products, not only energy, must be included to reach an acceptable performance in economic terms. A prerequisite is, however, the choice of crops that require low agricultural input, favor soil organic matter conservation, do not require irrigation and excess fertilizers.

If additional income from biorefinery products is achieved (also depending on market acceptance before becoming saturated), a small production of biodiesel from oil seeds is also possible and useful. Although bioenergy cannot be the main target of non-food cropping in marginal land, it could help achieve the process energy self-sufficiency. Furthermore, while bioenergy has a major difficult competitor in still cheap fossil fuels, a biorefinery chemistry is suitable to generate a large and diverse amount of chemical products, in so overcoming the possible demand saturation for some specific chemicals or biomaterials.

Products that are suitable for being used according to their information content (polymers, chemicals), i.e. according to the structure created by the photosynthetic process, should not be burnt as fuels, but must become the building blocks of innovative chemical patterns, alternative to fossil chemistry.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support received from the European Commission within the 7th Framework Program, Project no.217213, SMILE - Synergies in Multi-scale Inter-Linkages of Eco-social systems. Socioeconomic Sciences and Humanities (SSH) Collaborative Project FP7-SSH-2007-1.

REFERENCES

- Ballesteros, J.M. Oliva, M.J. Negro, P. Manzanares, M. Ballesteros. "Enzymic hydrolysis of steam exploded herbaceous agricultural waste (*Brassica carinata*) at different particle sizes". *Process Biochemistry* 38 (2002) 187-192.
- Bargigli S., 2002. Tesi di Dottorato (Ph.D. Thesis). *Analisi del Ciclo di Vita e Valutazione di Impatto Ambientale della Produzione ed uso di Idrogeno Combustibile*.
- Bargigli, S., Raugeri, M., and Ulgiati, S., 2005. "Mass flow analysis and mass-based indicators". In: *Handbook of Ecological Indicators for Assessment of Ecosystem Health*. Sven E. Jorgensen, Robert Costanza, and Fu-Liu Xu Editors. Pp. 353-378. CRC Press, 2005.
- Biondi P., Panaro V., Pellizzi G., 1989. *Le Richieste di Energia del Sistema Agricolo Italiano*. CNR, Consiglio Nazionale delle Ricerche, Progetto Finalizzato Energetica, Sottoprogetto Biomasse ed Agricoltura, Report LB-20, Roma, Italia.
- Boustead I., Hancock G.F., 1979. *Handbook of Industrial Energy Analysis*. New York, NY, USA: John Wiley & Sons Inc.
- Brown, M.T., and Ulgiati, S., 1999. "Emergy Evaluation of the Biosphere and Natural Capital". *Ambio*, 28(6): 486-493.
- Buonocore, E., Franzese, P.P., Ulgiati, S., 2010. "Emergy evaluation of an integrated bioenergy production system. The case study of Enköping (Sweden)". In: *Brown M.T., Campbell D., Comar V., Haung S.L., Rydberg T., Tilley D., Ulgiati S. (Eds.), EMERGY SYNTHESIS 6. Theory and Applications of the Emergy Methodology*. H.T. Odum Center for Environmental Policy, University of Florida, Gainesville, Florida, USA, January 12, 2010. (In press).
- Cleveland, C., and Costanza, R., 2008. "Energy return on investment (EROI)". In: *Encyclopedia of Earth*. Eds. Cutler J. Cleveland (Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment). [www.eoearth.org/article/Energy_return_on_investment_\(EROI\)](http://www.eoearth.org/article/Energy_return_on_investment_(EROI))
- CORINAIR, 2007. EMEP/CORINAIR Emission Inventory Guidebook – 2007; <http://www.eea.europa.eu/publications/EMEPCORINAIR5/>
- Davis Clement, L. and Van Dyne, D. L. 2006. "The Lignocellulosic Biorefinery-A strategy for Returning to a Sustainable Source of Fuels and Industrial Organic Chemicals". In : Kamm B., Gruber P.R. and Kamm M., *Biorefineries – Industrial Processes and Products (Status Quo and Future Directions)*, Volume I, Wiley-VCH, 2006.
- Fahd, S., Mellino, S., and Ulgiati, S., 2010. "Energy Cropping in Marginal Land: Viable Option or Fairie Tale?" In: D. Pimentel (Editor), *Global Economic and Environmental Aspects of Biofuels*. Taylor and Francis Publisher, In press.
- Herendeen R. 1998. "Embodied Energy, embodied everything... now what?" In: *Proceedings of the 1st International Workshop Advances in Energy Studies. Energy Flows in Ecology and Economy*, 13-48/642. MUSIS, Roma, Italy.
- Herendeen R.A., 1998. "Embodied Energy, embodied everything...now what?" In: *Advances in Energy Studies. Energy Flows in Ecology and Economy*. Ulgiati S., Brown M.T., Giampietro M., Herendeen R.A., and Mayumi K. (Eds). Musis Publisher, Roma, Italy; pp. 13-48.
- Hinterberger F. and Stiller H., 1998. "Energy and Material Flows". In: *Advances in Energy Studies. Energy Flows in Ecology and Economy*. Ulgiati S., Brown M.T., Giampietro M., Herendeen R.A., and Mayumi K. (Eds). Musis Publisher, Roma, Italy; pp.275-286.
- Lazzeri, L., O. Leoni, L. D'Avino, L. Malaguti. "Biorefinery – Brassicaceous plants as more than biofumigants! Third International Biofumigation" *Symposium. CSIRO Discovery Centre, Canberra, Australia (2008)*.
- Leiden, 2000. CML2 - Centre of Environmental Science, Leiden University, NL. http://www.pre.nl/simapro/impact_assessment_methods.htm#CML2
- Lichtenthaler F., 2006. "The Key Sugars of Biomass : Availability, Present non-Food Uses and Potential Future Development Lines". In: Kamm B., Gruber P.R. and Kamm M., *Biorefineries – Industrial Processes and Products (Status Quo and Future Directions)*, Volume II, Wiley-VCH, 2006.
- Murthy G.S., Sridhar, S., Shyam, M., Sunder, Shankaraiah, B., Ramakrishna, M. 2005. "Concentration of xylose reaction liquor by nanofiltration for the production of xylitol sugar alcohol. Separation and Purification" *Technology* 44 (2005) 205–211.
- Odum H.T., 1988. "Self organization, transformity and information". *Science*, 242: 1132-1139.
- Odum H.T., 1996. *Environmental Accounting. Emergy and Environmental Decision Making*. John Wiley & Sons, N.Y.

- Ritthoff, M., Rohn, H., and Liedtke, C., 2003. *Calculating MIPS. Resource Productivity of Products and Sources*. Wuppertal Institut for Climate, Environment and Energy – Science Centre North Rhine-Westphalia. ISBN 3-929944-56-1e. Pp.53.
- Schilling, L.B. "Chemicals from alternative feedstock in the United States". *FEMS Microbiology Reviews*, 16 (1995) 1001-1110.
- Schmidt-Bleek, F., 1993. "MIPS re-visited". *Fresenius Environ. Bull.* 2, 407–412.
- Slesser, M., 1974. *Energy analysis workshop on methodology and conventions*. Report IFIAS No. 89. Stockholm: International Federation of Institutes for Advanced Study.
- Ulgati S., Raugei M., and Bargigli S., 2006. "Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment". *Ecological Modelling*, 190: 432–442.
- Ulgati S., 2001. "A Comprehensive Energy and Economic Assessment of Biofuels: When "Green" Is Not Enough". *Critical Reviews in Planet Science*, 20 (1), pp. 71-106.
- Ulgati, S., Brown, M.T., Bastianoni, S., and Marchettini, N., 1995. "Emergy based indices and ratios to evaluate the sustainable use of resources". *Ecological Engineering*, 5(4), 519-531.
- Ulgati, S., Raugei, M. and Bargigli S., 2006. "Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment". *Ecological Modelling*, 190: 432–442.
- US-EPA, 2010. *Compilation of Air Pollutants Emission Factors*, Volume I, Fifth Edition, Point Sources AP-42. U.S.A. Environmental Protection Agency. <http://www.epa.gov/ttnchie1/ap42/>
www.bioeconomyconference.org/conf2005/Presentations/Tom_Robb.pdf

VIABILITY OF BIOFUELS AS INFLUENCED BY AGRICULTURAL PRODUCTION SYSTEM

Hanne Østergård and Mads Ville Markussen*

*Risø National Laboratory for Sustainable Energy DTU,
Technical University of Denmark, Roskilde, Denmark*

ABSTRACT

Governments all over the world see bioenergy as a substantial contributor to energy supply in a future biobased economy. This view is, however, not without problems as the energy delivered by biofuels is often not significantly higher than the energy used directly or indirectly in the process to produce them taking the agricultural production into account. The Energy Return on Investment (EROI) has in many studies been found to be less than 3:1 and an energy source with an EROI of this order does not qualify as a main energy source for an industrialized economy as we have today. However, if production of biofuels is integrated into a low-input or organic crop production system with focus on energy self-sufficiency, recycling, soil fertility building and biodiversity, then bioenergy may provide a valuable contribution to future energy supply and, just as important, an increased resilience of food supply systems.

The EROI does not distinguish between input from renewable and non-renewable energy sources, as well as how much the process takes advantage of nature's work. Emergy accounting is a method to include these aspects by summarizing the work of nature and of the economy into one unit, solar emergy joules (sej) while keeping track of the source and renewability of all inputs. Different emergy indices quantify in different ways the contribution of renewable resources and the return in emergy terms compared to the investment, e.g. the emergy yield ratio. By combining net energy analysis and emergy accounting, a better characterization of the viability of a specific biofuel and its co-products can be obtained.

As starting point, we model a small-scale Danish stockless organic farming system. This system, with 40% of land grown with energy crops providing fertilizer and feed as co-products and 40% of land grown with nitrogen fixing crops, is self-sufficient with energy (biodiesel, electricity and heat) and nitrogen fertilizer and, in addition, provides food, feed and bioenergy to the society. The input needed is land, labour, services, replacement of machinery and in the longer run input of potassium and phosphorus fertilizers. This kind of system being realistic also in future energy scenarios is, however, not nearly sufficient at a large scale to sustain the current Danish consumption pattern of neither energy nor food.

We compare this system with published analyses of systems producing biodiesel, biogas or bioethanol in different agronomical contexts worldwide. All systems will be characterized according to, e.g., system boundary, high or low-input growing conditions, energy self sufficiency, level of recycling and type of co-products. Based on this, we discuss the viability of each system using emergy indices and simple net energy analyses. Hopefully, this will contribute to broaden the discussion on potentials of bioenergy from a future agriculture based on integrating biofuels and food production in sustainable production systems.

Keywords: biofuels, net energy analysis, emergy accounting, agricultural production

* Presenting author: Hanne Østergård (haqs@risoe.dtu.dk)

ENERGY AND EMERGY EVALUATIONS OF AGRICULTURAL AND FARMING PRODUCTION SYSTEMS IN THE TOLEDO RIVER BASIN (BRAZIL)

Otávio Cavalett¹, Salvatore D'Angelo^{1,2}, Pier Paolo Franzese^{*1}

¹ *Department of Environmental Sciences, Parthenope University of Naples, Italy*

² *UNESCO, Division of Water Science, Paris, France*

ABSTRACT

In this paper we explore the environmental performance and sustainability of soybean-corn intercrop and swine production systems in the Toledo river basin (Brazil). The main steps of the case study were: (a) modeling of selected agricultural and farming production systems by means of Odum's energy-symbolic language; (b) development of calculation procedures to assess the main matter, energy, and money flows supporting the investigated systems; (c) assessment of the environmental performance in terms of energy, emergy, and water use per unit of generated products; (d) assessment of the environmental impact in terms of CO₂ released per unit of generated products; (e) calculation of indicators of environmental sustainability. These indicators were calculated at farm scale and then upscaled at basin level to assess the load of the investigated production processes at regional level. The use of water for such intensive agricultural and farming systems, the manure concentration as well as the relationships between the increasing impact of human-dominated production activities and effects of climate change in the region are also discussed in the paper. Results show that a multicriteria environmental accounting provides useful information to support local policy makers committed to develop policies for a sustainable use of natural resources. The methodological approach also provided a better understanding of the role played by natural capital and ecosystem services in relation to the investigated agroecosystem.

Keywords: Energy, Emergy, Water, CO₂, Swine, Soybean, Corn, Toledo, Brazil

1. INTRODUCTION

The Toledo river basin is located in the south-western portion of the Paraná state. Underlain by the Guarani aquifer, the Toledo river basin has a very high potential for groundwater use. The basin is characterized by both intensive farming and agricultural production processes, among which the most important are swine and soybean-corn intercrop productions. Most of the manure produced by the swine rearing systems is used to fertilize the soil with little or no treatment (Kunz et al., 2009). Such a practice generates a set of environmental impacts due to the excess of manure produced by the intensive swine production systems in the region (Tomm, 2001; Winter et al., 2005; Nieweglowski, 2006). The soybean-corn intercropping system, often fertilized with manure, represents the most important cropping system in the basin. These crops are also determining the pollution of groundwater due to the intensive use of agrochemicals (Nieweglowski, 2006).

Both agricultural and farming systems are generating a massive use of groundwater and water pollution phenomena. Over time, the cumulative application of manure and agrochemicals as well as the urban sprawl could lead to severe groundwater pollution.

In such a context, it is crucial to assess the environmental performance and sustainability of the local agroecosystem by exploring the following features: yield, resource use and efficiency, local versus imported resource use, renewable versus non-renewable resource use, environmental load and sustainability, interaction and

* Corresponding author; E-mail: pierpaolo.franzese@uniparthenope.it

dependence on the local environment. In particular, a special attention should be given to groundwater use in support to agricultural and farming systems and concentration of manure in the basin.

The main goals of the study were: (1) modeling of selected agricultural and farming production systems by means of Odum's energy-symbolic language; (2) development of calculation procedures of environmental accounting to assess the main matter, energy, and money flows supporting the production systems; (3) assessment of the environmental performance in terms of energy, emergy, and water use per unit of generated products; (4) assessment of the environmental impact in terms of CO₂ released per unit of generated products; (5) calculation of indicators of environmental sustainability.

Intensive indicators calculated at farm scale were upscaled at basin level to assess the load of the investigated production processes at regional level. The relationships between the increasing impact of human-dominated activities and climate change are also discussed in the paper.

2. MATERIALS AND METHODS

2.1 The Toledo River Basin

The Toledo river basin is located in the south-western portion of the Paraná state and has a length of about 27 km, covering an area ranging from 24°43' to 24°47' south latitude and from 53°33' to 53°45' west longitude. With a population of approximately 550 inhabitants, the basin has a total area of 9292 ha, enclosing the following land use categories: agriculture 69.5%; urban area 16.4%; forest 12%; pasture 1.7%; water 0.3% (Tomm, 2001; Winter et al., 2005).

The Toledo river represents an important water source, exploited to supply 40% of the population of the town of Toledo. The Toledo basin accounts for only 4.2% of the area of Paraná state, but it plays an important role also in relation to the reservoir of the Itaipu Binacional dam. Characterized by both intensive agricultural and farming activities, among which the most important are swine and soybean-corn intercrop productions, the basin holds 195 farms, 46 of which include swine production activities (Winter et al., 2005).

In the last decades, the intensification of swine production systems has been characterized by the use of smaller areas, industrial feed stuffs, and the massive use of fossil energy in all the stages of the production processes, such as installations, feeding, medicaments, and transport. The huge concentration of swine farms in some areas, together with coal extraction and the wide use of agrochemicals, has originated a severe threat to the Guarani aquifer: the biggest water source of South America (Pinheiro Machado Filho et al., 2001).

The soybean-corn intercropping systems are an important source of income for the local economy but also generate water pollution due to the high use of agrochemicals and fertilizers. While soybean is produced in the basin over the summer, corn (or wheat) is cropped in the same areas during the other seasons. Corn and soybean are mostly sold to the market to be industrialized and used in the formulation of swine feed stuffs.

These modern practices for agricultural and swine production rely on high direct and indirect use of fossil fuels (diesel, machinery, fertilizers, agrochemicals, etc.). The massive use of non-renewable resources generated a high pressure on the agroecosystem, lowering the sustainability of these production activities (Ortega et al., 2005; Cavalett and Ortega, 2009; Cavalett et al., 2006).

2.2 Embodied Energy Analysis

The Embodied Energy Analysis (EEA) has been defined as the process of determining the energy required directly and indirectly to allow a system to produce a good or service (IFIAS, 1974). The Gross Energy Requirement (GER) method accounts

for the amount of fossil energy (also referred to as commercial energy) required directly and indirectly to make a good or service (Slesser, 1978; Smil, 1991; Herendeen, 1998; Franzese et al., 2009a). The GER method is concerned with the depletion of fossil fuels and it focuses the attention on the availability and use of fossil and fossil-equivalent energy invested to produce a product or service.

Direct use of fossil fuels refers to oil, lubricants, and electricity, while indirect use of fossil fuels is related to structures, machinery, fertilizers, pesticides, chemicals, among others.

In the GER method, all inputs to the process are multiplied by an energy intensity factor accounting for the amount of fossil resources directly and indirectly required to produce them. The total of such fossil and fossil-equivalent energy requirement represents the GER of the process while the ratio between the GER of the process and the amount of generated product provides the GER of the product (usually expressed in MJ per kg).

Renewable resources provided for free by the environment (without using any fossil energy to make them available) are not accounted for by GER method. Human labor and economic services are also not included in most evaluations (Franzese et al., 2009a).

2.3 Emergy Synthesis

The Emergy Synthesis method (Odum, 1988, 1996) is an energy evaluation method aimed at calculating indicators of environmental performance and sustainability accounting for both natural and economic resources used up within natural ecosystems and human-dominated processes (Brown and Ulgiati, 1999; 2004a,b; Cavalett et al., 2006; Franzese et al., 2008a,b; 2009a,b; Ulgiati et al., 2006, 2008, 2010a,b,c).

According to the emergy theory, different forms of energy, materials, human labor, and economic services are all evaluated on the common basis of biosphere by converting them into equivalents of only one form of energy, the solar kind, expressed as solar equivalent Joule (seJ). To be more specific, emergy is defined as “the total amount of available energy of one kind (most often of the solar kind) that is used up directly or indirectly in a process to deliver an output product, flow, or service” (Odum, 1996).

The Emergy method evaluates the environmental performance and sustainability of systems on the global scale of biosphere, taking into account the free environmental inputs (solar radiation, wind, rain, geothermal, etc.), resources coming from the economy, as well as the indirect environmental support embodied in human labor and economic services, usually not included within conventional energy analyses and economic evaluations (Franzese et al., 2009a). In so doing, the Emergy method accounts for the past and present environmental support to a process and it allows to explore the interplay of natural ecosystem and human activities.

In this study, we used the new emergy baseline for biosphere of $15.83 \cdot 10^{24}$ seJ/yr (Brown and Ulgiati, 2004b) and all the emergy intensity factors (specific emergy and solar transformity factors) were updated to such baseline.

3. RESULTS AND DISCUSSION

Money, energy, material, and water requirements of an average farm integrating corn, soybean, and swine production systems were evaluated through the development of a detailed environmental accounting. The raw data used to implement the calculation procedures¹ were obtained from literature, statistical books, and field interviews to the farmers.

The main inputs and outputs of the soybean-corn intercrop production system were accounted for one hectare of an average farm located in the Toledo basin.

At the same way, the main inputs and outputs of the swine production system were accounted for an average swine farm located in the Toledo river basin and producing 650

heads per year. The farmed animals are usually delivered to the processing industry with an average weight of 110 kg after 120 days in the rearing system.

Figure 1 shows the energy system diagram drawn to model the investigated systems. Such a qualitative model, drawn according to a standardized energy systems language (Odum, 1996), was used as a basis to develop the quantitative inventory of input and output flows. The symbolic model shows in a pictorial way the system boundary, the main driving forces, producers, consumers, storages, and interactions among system's components. According to Odum (1996), driving forces and system's components were drawn from left to right in order of increasing energy quality (*i.e.*, increasing transformity) to provide a reference to the energy hierarchy characterizing the investigated system. Based on the system diagram, tables of input flows supporting agricultural and farming systems were identified, quantified, and converted to energy and emergy unit by means of suitable intensity factors. Finally, a set of indicators were calculated to explore the environmental performance and sustainability of the investigated production activities.

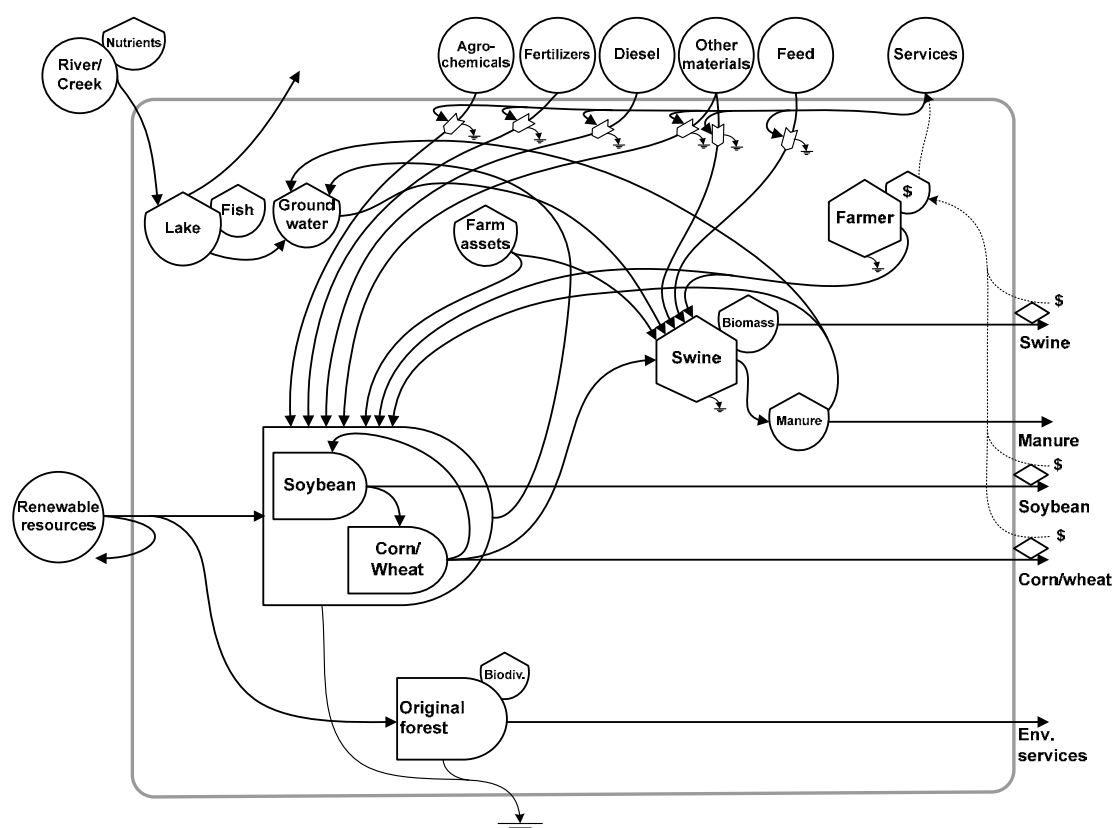


Figure 1. Energy systems diagram of a typical farm in the Toledo river basin (Brazil) integrating both swine and soybean-corn production systems.

Table 1 summarizes the indicators of environmental performance calculated for swine, soybean, and corn production systems in the Toledo river basin, Brazil.

Table 1. Indicators of environmental performance calculated for swine, soybean, and corn production systems in the Toledo river basin (Brazil).

Indicator	Swine (meat)	Soybean	Corn
Total fossil energy use (J/ha/yr)	5.65E+11 ^a	3.72E+09	9.77E+09
Total emergy use (seJ/ha/yr)	5.84E+17 ^a	6.03E+15	7.86E+15
Yield, energy output (J/ha/yr)	6.59E+11 ^a	5.96E+10	1.22E+11

Yield, mass output (kg/ha/yr)	71,500 ^a	3,000	7,452
EROI	1.17	16.02	12.50
CO ₂ equivalent emissions (kg CO ₂ eq / kg)	0.60	0.17	0.10
Water demand (kg water / kg)	19.85	3.08	1.45
Solar transformity (seJ/J)	8.87E+05	1.00E+05	6.38E+04
Specific emergy (seJ/kg)	8.17E+12	1.99E+12	1.05E+12
Emergy Yield Ratio	1.00	1.66	1.42
Environmental Loading Ratio	3,727	2.33	3.35
Renewability (%)	0.03	30.02	22.98
Empower Density (seJ/m ² /yr)	6.68E+14	5.97E+11	7.80E+11

^a Unit for swine production system are calculated per year (instead of per hectare per year as in the case of soybean and corn productions).

3.1 Performance and sustainability indicators at farm level

Table 1 shows that about 0.03 kg of crude oil equivalent were used to produce 1 kg of soybean, that translates into an Energy Return On Investment (EROI) of 16.02 (about 16 joule of soybean were produced per joule of fossil fuel invested in the production process). As a consequence, 0.17 kg of CO₂ were emitted per kg of soybean produced.

About 0.03 kg of crude oil equivalent were also used to produce 1 kg of corn, with an EROI of 12.50. The carbon dioxide emissions accounted for 0.10 kg CO₂ per kg of corn produced.

Finally, 0.19 kg of oil equivalent were used to produce 1 kg of swine meat, equal to an EROI of 1.17. The carbon dioxide emissions accounted for 0.6 kg CO₂ per kg of swine meat produced.

The Water Demand shows that swine production system used (directly and indirectly) about 20 l of fresh water per kg of swine meat produced. This figure pointed out that swine production systems are characterized by a very intensive water demand with a serious potential impact on availability and quality of water resource in the Toledo river basin.

The solar transformity for swine meat ($8.87 \cdot 10^5$ seJ/J) resulted much higher than the solar transformity for corn ($6.38 \cdot 10^4$ seJ/J) and soybean ($1.00 \cdot 10^5$ seJ/J), indicating that the swine system required a bigger global environmental support to produce 1 joule of product. These results confirmed that swine production subsystem occupies a higher position within the energy hierarchy of the whole integrated process due to its feature of animal production system.

Swine production subsystem was supported by a very small contribution of renewable resources; for this reason it could be considered like an industrial activity that is supported almost exclusively by human-driven economic resources coming from outside the system. The intensification of swine production over the last decades using smaller areas and industrial feed stuffs has been based on the massive use of fossil energy in all the steps of the production process. This situation was also reflected by the very high Environmental Loading Ratio (3727) and very low Emergy Yield Ratio (1.00) calculated for swine production system.

Soybean production subsystem showed a renewability of 30%. This means that 70% of the inputs supporting the process were related to non-renewable sources of energy. The same indicator for corn production subsystem was even lower: 22.98%.

The density of emergy use over time is shown by the Empower Density (ED) (Table 1). The ED of swine production subsystem ($6.68 \cdot 10^{14}$ seJ/m²/year) resulted much higher than the ED of soybean ($5.97 \cdot 10^{11}$ seJ/m²/year) and corn ($7.80 \cdot 10^{11}$ seJ/m²/year) subsystems, highlighting how swine production subsystem is much more intensive in the use of resources per unit of area than the investigated agricultural crops.

3.2 Performance and sustainability indicators at basin level

Indicators calculated at farm level were upscaled at basin level to assess the environmental impacts at regional scale. The Toledo basin is characterized by an agricultural area of 6,460 ha cropped with soybean-corn intercrop and a farming area producing about 11,000 swine per year.

The three production systems require an annual use of about $9.67 \cdot 10^{13}$ J of fossil energy. Such total use of fossil energy determines an annual release of 8,831 t of CO₂ equivalent.

Considering an average water use of 143 l/person/day in urban areas of Brazil, the amount of fresh water directly and indirectly used for soybean, corn, and swine productions in the Toledo river basin (excluding water from rain) is equivalent to the water supply for a city with 3,015 inhabitants. This last figure is about 5.5 times higher than the population living in the Toledo river basin.

Soybean, corn, and swine production systems require $9.88 \cdot 10^{19}$ seJ/year. If this emergy flow could be provided only by renewable resources (rain), it would be necessary an area equivalent to 58,477 ha. This value is about 6.3 times higher than the total area of the basin (considering all land uses in the basin).

These results prove the high intensity of energy, water, and emergy use due to agricultural and farming activities in the Toledo river basin. These footprints are exceeding the carrying capacity of the Toledo basin and are sustained by eroding the stocks of natural resources at an unsustainable rate.

3.3 Sustainable management of manure in the Toledo river basin

The Toledo river basin hosts 47 farms producing about 11,000 swine heads per year. They produce approximately 150,000 l of manure per day. Literature shows that a swine produces a daily amount of manure equivalent to about 10 people (Winter et al., 2005). Following this parallel, the swine of the Toledo basin would be equivalent to a population of 110,000 inhabitants (in a basin with an actual population of only 550 inhabitants).

Seganfredo (2000) estimated that one swine produces about 12 kg of nitrogen per year; this means that the 11,000 swine per year raised in the Toledo basin generate 132,500 kg of nitrogen. Taking into consideration the UN recommendation about the manure spread of 170 kg of nitrogen per hectare per year (European Council Regulation, 1999), it would be necessary an area of about 780 ha in the basin to dispose of the produced manure avoiding environmental problems. In theory this land surface would be available since the basin has an agricultural area of about 6460 ha. However, by dividing the necessary agricultural area for the 47 farms having swine production in the basin, it would be necessary about 17 ha of agricultural area for each farm to dispose of the manure. These figures highlight the problem of lack of available agricultural land for manure spread due to the fact that the 72% of the farms located in the Toledo basin are characterized by less than 20 ha of land (Winter et al., 2005). Moreover, according to the Brazilian Forestall Law, all the farms in this area of Brazil should preserve at least 20% of the area with original forest. All this resulted in the accumulation of manure in soil and water bodies with all the related environmental problems. The inadequate management of swine manure can contribute to methane and nitrous oxide emissions in the atmosphere, gases well known for their strong contribute to global warming. For instance, each molecule of methane has a potential contribution to global warming effects equivalent to 24 molecules of CO₂ (IPCC, 2001).

This scenario requires the improvement of new policies ensuring the sustainable management of agricultural and farming activities characterizing the economic dynamics of the Toledo river basin.

4. CONCLUSIONS

The multicriteria approach used to develop this case study provided useful information about the interactions and proper use of natural capital, human-driven resources, and ecosystem services supporting the management of agricultural and farming systems in the Toledo river basin (Brazil). The indicators of environmental performance highlighted the intensification process occurring in the basin over the last decades. The indicators of environmental sustainability showed an increased dependence on non-renewable resources (mainly from outside the system) supporting modern agricultural and farming production processes.

Crucial factors worth to further investigations are the high use of water and concentration of manure, both due to the high density of agricultural and farming activities.

In conclusion, the methodological approach used in this study and related multidisciplinary set of indicators can provide a benchmark for future investigations as well as an useful support to local policy makers committed to develop environmental policies based on the sustainable management of agroecosystems.

Note

1. Calculation procedures were not included in the paper due to space restrictions but are available on request from authors.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of UNESCO-IHP in the framework of the project "Water Program for Environmental Sustainability". Authors are also grateful to Rafael González from the International Hydroinformatics Center (PTI Itaipu) for providing data and assistance to set up the case study.

REFERENCES

- [1] Brown, M.T., Ulgiati, S. 1999. "Emergy evaluation of the biosphere and natural capital". *AMBIO* 28, 486–493.
- [2] Brown, M.T., Ulgiati, S. 2004a. "Energy quality, emergy, and transformity: H.T. Odum's contribution to quantifying and understanding systems". *Ecological Modelling*, 178: 201–213.
- [3] Brown, M.T., Ulgiati, S. 2004b. "Emergy analysis and environmental accounting". In: Cleveland C, editor. *Encyclopedia of emergy*. Oxford, UK: Academic Press, Elsevier; p. 329–354.
- [4] Cavalett, O., Ortega, E., 2009. "Emergy, nutrient balance, and economic assessment of soybean production and industrialization in Brazil". *Journal of Cleaner Production* 17(8): 762–777.
- [5] Cavalett, O., Queiroz, J. F., Ortega, E., 2006. "Emergy assessment of integrated production systems of grains, pig and fish in small farms in the South Brazil". *Ecological Modelling*, 296: 205–224.
- [6] European Council Regulation. 1999. *Official Journal of the European Community* v. 42, n. 1804/1999. Available at: <http://www.europa.eu.int/eurlex/en/archive/1999/L22219990824en.html>
- [7] Franzese, P.P., Russo, G.F., Ulgiati, S., 2008a. "Modeling the interplay of environment, economy and resources in marine protected areas. A case study in southern Italy". *Ecological Questions*, 10: 91–97.
- [8] Franzese, P.P., Russo, G.F., Ulgiati, S., 2008b. "GIS and Emergy Synthesis evaluation of urban waste management". In: Barbir, F. and Ulgiati, S. (Eds.), *Sustainable Energy Production and Consumption. Benefits, Strategies and Environmental Costing*. Book of the NATO Series: Science for Peace and Security, 339–352. Springer.
- [9] Franzese, P.P., Rydberg, T., Russo, G.F., Ulgiati, S., 2009a. "Sustainable biomass production: a comparison between Gross Emergy Requirement and Emergy Synthesis methods". *Ecological Indicators*, 9: 959–970.

- [10] Franzese, P.P., Arico, S., Viglia, S., Russo G.F., Ulgiati, S., 2009b. "Emergy-based evaluation of natural capital and ecosystem services: the case study of Astroni Wildlife Reserve, Italy". In: Brown M.T., Campbell D., Comar V., Haung S.L., Rydberg T., Tilley D., Ulgiati S. (Eds.), *EMERGY SYNTHESIS 5. Theory and Applications of the Emergy Methodology*. Center for Environmental Policy, University of Florida, Gainesville, USA, pp. 55-64 (ISBN: 978-0-9707325-4-5).
- [11] Herendeen, R., 1998. "Embodied energy, embodied everything... now what?" In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A. and Mayumi, K. (Eds.), *Book of Proceedings of the International Workshop "Advances in Energy Studies. Energy Flows in the Ecology and Economy"*, Porto Venere, Italy, May 26/30, 1998, pp. 13–48.
- [12] IFIAS. 1974. *Emergy analysis*. Workshop Report no. 6. Stockholm, 89 pp.
- [13] IPCC, 2001. Climate Change 2001: "The scientific basis". In: Houghton J.T., Ding Y., Griggs D.J., Noguer M., van der Linden P.J., Dai X., Maskell K., Johnson C.A., (eds). *Contribution of working group I to the third assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
- [14] Kunz, A., Miele, M., Steinmetz, R.L.R., 2009. "Advanced swine manure treatment and utilization in Brazil". *Bioresource Technology*, 100: 5485–5489.
- [15] Nieweglowski, A.M.A., 2006. *Indicadores de qualidade da água na bacia hidrográfica do rio Toledo – PR*. Master thesis in Agronomy. State University of Paraná. 237pp.
- [16] Odum, H.T., 1988. "Self-organization, transformity, and information". *Science*, 242: 1132–1139.
- [17] Odum, H.T., 1996. *Environmental accounting. Emergy and environmental decision making*. NY: John Wiley & Sons, p. 370.
- [18] Ortega, E., Cavalett, O., Bonifacio, R., Watanabe, M., 2005. "Brazilian Soybean Production: Emergy Analysis With an Expanded Scope". *Bulletin of Science, Technology & Society*, 25 (4): 323-334.
- [19] Pinheiro Machado Filho, L.C., da Silveira, M.C.A.C., Hötzel, M. J., Pinheiro Machado, L.C., 2001. "Produção agroecológica de suínos – uma alternativa sustentável para a pequena propriedade no Brasil". *II Conferência Internacional Virtual sobre Qualidade de Carne Suína*. Available at: <http://www.freewebs.com/hotzel/Suino%20Organico%202001.pdf>
- [20] Segnfredo M. A. 2000. *Equação de dejetos. Suinocultura Industrial*, Seção: Informe Técnico. No.144 abr/mai Ano 22, pp. 14 - 18.
- [21] Slesser M, 1978. *Emergy in the Economy*, London, Macmillan.
- [22] Smil, V., 1991. *General Energetics: Emergy in the Biosphere and Civilization*. John Wiley and Sons, New York, USA, 369 pp.
- [23] Tomm I. 2001. *Avaliação da qualidade da água do Rio Toledo (Toledo – Paraná) através de macroinvertebrados bentônicos*. Master thesis in Production Engineering State University of Santa Catarina. Florianópolis, SC, Brazil. 224 pp.
- [24] Ulgiati, S., Raugei, M., Bargigli, S. 2006. "Overcoming the inadequacy of single-criterion approaches to Life Cycle Assessment". *Ecological Modelling*, 190: 432-442.
- [25] Ulgiati, S., Zucaro, A., Franzese, P.P., 2008. "Matter, energy and emergy assessment in the agricultural sectors of the campania region. Constrains, bottlenecks and perspectives". In: Schnitzer H., Ulgiati S. (Eds.). *Advances in Energy Studies: Towards a holistic approach based on science and humanity*. Graz University of Technology, Austria, pp. 550-560.
- [26] Ulgiati S., Zucaro, A., Franzese, P.P., 2010a. "Shared Wealth or Nobody's Land? The Worth of Natural Capital and Ecosystem Services". Submitted to *Ecological Economics*. In review.
- [27] Ulgiati, S., M. Ascione, S. Bargigli, F. Cherubini, M. Federici, P.P. Franzese, M. Raugei, S. Viglia, A. Zucaro, 2010b. "Multi-method and multi-scale analysis of energy and resource conversion and use". In: Barbir, F. and Ulgiati, S. (Eds.), *Emergy Options Impacts on Regional Security*. Book of the NATO Series: Science for Peace and Security, Springer. Accepted for publication. In Press.
- [28] Ulgiati, S., Ascione M., Bargigli S., Cherubini F., Franzese, P.P., Viglia, S., Zucaro, A., 2010c. "Material, Emergy and Environmental Performance of Technological and Social Systems under a Life Cycle Assessment Perspective". *Ecological Modelling*. Accepted for publication. In press.
- [29] Winter, R., Braun, M.B.S., Lima, J.F.L., 2005. *Notas sobre o impacto da produção de suínos na Bacia do Rio Toledo – PR*. UNIOESTE, Available at: <http://www.sober.org.br/palestra/2/427.pdf>

RADIATIVE FORCING IMPACTS OF BOREAL FOREST BIOFUELS: A DYNAMIC STUDY FOR NORWAY IN LIGHT OF ALBEDO

Ryan M. Bright^{*1}, Anders. H. Strømman¹, Glen P. Peters²

¹ *Industrial Ecology Program, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway*

² *Center for International Climate and Environmental Research – Oslo (CICERO), Norway*

ABSTRACT

Recent policies of Nordic Europe lend support to expanded use of boreal forest resources for climate mitigation objectives. Many are often guided by research limited to the carbon cycle and to reductions in atmospheric CO₂ concentrations, although it is becoming increasingly demonstrated in the scientific literature that biophysical land surface factors can influence climate through a variety of other mechanisms. In high latitude boreal regions with significant annual snow cover, like Norway, land surface albedo has been shown to be the dominant biophysical factor in direct opposition to the carbon cycle. It is therefore important to attribute this so-called “albedo effect” to the climate balance of the forestry sector and to forest product systems like biofuels.

Perturbations to the global radiation budget prior to any feedbacks, such as changes in land surface albedo, can be compared directly with the effects of the carbon cycle through the concept of radiative forcing. Our main objective is to assess the radiative forcing impact due to a changing surface albedo when forests in Norway are harvested more intensively for biofuels. This impact is compared and added to that associated with changes in the forest carbon cycle and avoided life cycle fossil fuel emission.

Our framework integrates life cycle emission data together with a dynamic land use model that tracks carbon flux and area changes in productive forests over a 100-yr. time horizon. Land use carbon accounting follows the “Gain-Loss” method of the IPCC. MODIS surface albedo data is used together with climatic information on cloud cover and cloud properties to estimate local net shortwave radiation fluxes at the top of the atmosphere (ΔSW_{TOA}) over productive forest areas. Radiative forcing from albedo change at any given time step is the difference in the global ΔSW_{TOA} flux between a control scenario and a biofuel scenario. Instantaneous forcing is both integrated over time and converted into annual CO₂-eq.-emission pulses.

Depending on the albedo uncertainty, and uncertainty about the geographic distribution of future logging activity, we report a range of results, thus only general conclusions about the magnitude of the carbon offset potential over time due to changes in surface albedo can be drawn. Nevertheless, our results have important implications for how forests might be managed for mitigating climate change in light of this additional biophysical criterion, and in particular, on future biofuel policies throughout the region. Future research efforts should be directed at understanding the relationships between the physical properties of managed boreal forests and albedo, and how albedo changes in time as a result of specific management interventions.

Keywords: biofuel, forest, albedo, climate impact, carbon

* Corresponding author; E-mail: ryan.m.bright@ntnu.no; Phone: +47 73 59 89 72

INDICATORS, EMERGETIC THRESHOLDS AND CONSTRAINTS FOR COASTAL SPATIAL PLANNING AND MANAGEMENT

Leonardo Marotta^{*1}, Lorenzo Benini², Luciano Vogli², Vittoria Bandini²,
Gianmario Deandrea¹, and Diego Marazza²

¹ ENTROPIA S.N.C. di L. Marotta & C, via Corridoni 3, 62019, Recanati, Italy

² Interdepartmental Centre for Research in Environmental Sciences - CIRSA,
University of Bologna, Via Sant'Alberto 163, 48123 Ravenna, Italy

ABSTRACT

The article describes the method chosen for the definition of a development scenario and a set of indicators for integrated coastal zones management. The case studies are in the Center and North Adriatic Sea (Italy, Mediterranean Sea). Selected areas are the Lagoon of Venice, the Province of Rimini and the Conero coastal area. The development of indices and indicators set focuses on sub-regional and local sustainability of coastal management. A multi-scale and diachronic approach based on landscape and seascape ecology is build in order to develop the dynamics of indices set. The indices results are the threshold for carbon, ecological and space footprints.

The used approach provides the following results: identification of conflicts and urban sprawl, assessment of degree of sustainability (carbon footprint, ecological footprint, emergy and LDI), assessment of change during the last 30 years. Indicators are developed dealing with both landscape ecology and health of ecosystems. Modeling these changes is critical for formulating effective environmental policies and management strategies. The developed model provides suitability maps per each area in order to maximize different policy objectives reducing the coastal conflicts. A final scenario is proposed and assessed in each case studied.

Keywords: Integrated coastal zone management, Indices, MCA, emergy synthesis

1. INTRODUCTION

Can we break the addiction to fossil energy? That depends also on land use planning. Transports, household consumption, facilities and urban infrastructures shape the energy demand and deeply affect the shifting to renewable energies. Coastal zones incur nowadays a quick change of land uses and require a watchful planning and management. The *integrated coastal zone management* (ICZM) can be seen as a major contribution for the coastal policies inside the definition of European goals as well as in the governance of world coastal spaces. The ICZM and Marine spatial planning policies act across spatial levels and permits an integration with other spatial policies (national, EU, regional, global) and domains [Encora network 2008, DEFRA 2006]. The principal aim on the process of these planning policies is the achievement of Sustainable Development: ecosystem conservation, social equity, efficiency of economy [Vallega, 1999]. The environmental sciences, taking into account the relationship between the man and the ecosystem and their common services, brings up the concept of the Ecosystem Approach [CBD, 2000] and the concept of resilience and adaptive change in social-ecological systems [Gunderson and Holling, 2002; Gunderson *et al.*, 2009]. ICZM needs tools in order to deal with interdisciplinarity, multiple scales (e.g., spatial, temporal or organizational) and the different actors participating to the multilevel coastal governance [COM(2000)547; COM(2005)504 final; COM(2005)505; COM(2007)0308 final]. The Integrated Maritime Policy for the European Union served as an important factor in

* Corresponding author; E-mail: leonardo.marotta@entropia-env.it; Tel. +393383518558

stimulating consolidation of coastal and marine information to support policy implementation [Meiner, 2009], based on indicators, indices (aggregations of indicators into a single representation), *geographic information systems* (GIS), models, scenarios and *multicriteria assessment* (MCA) for decision support [Vallega 1999; Soncini Sessa 2004; Munda 2003; 2004; Ortolano 1997; Van Kouwen et al. 2008]. Indices are used to describe the coastal system at a geo-ecological level, modeling earth processes, ecology, human society and economy, and coastal uses at multiple scales [Vallega 1999].

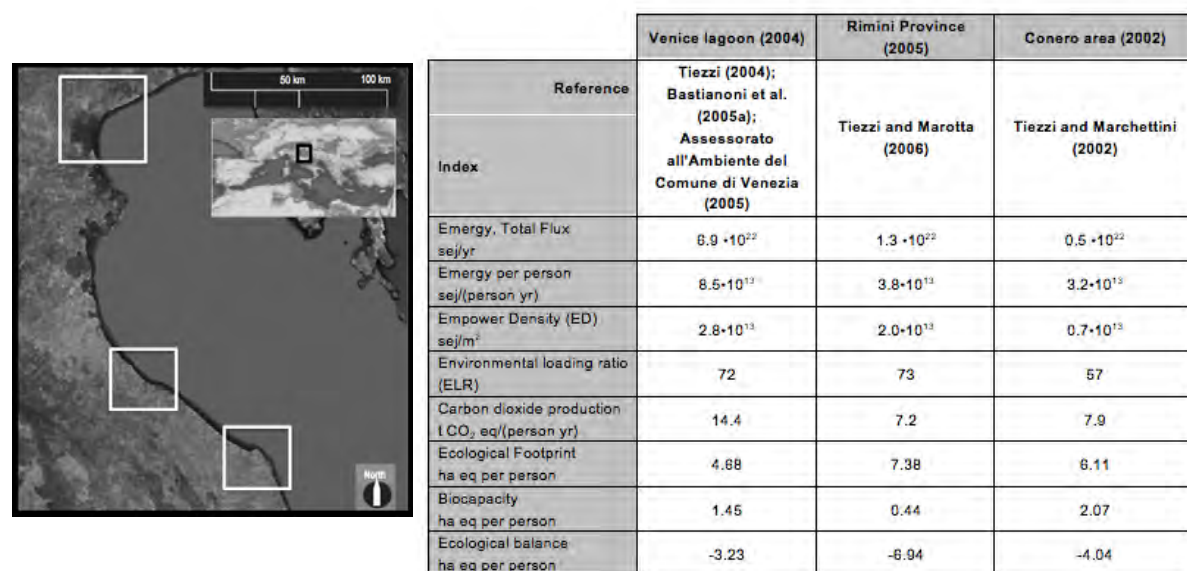


Figure 1. Study areas, from north to south: Venice Lagoon, Rimini Province, Conero area (Ancona Province). On the right, the basic data used for the study areas.

This contribution outlines the goals and constraints that land use planning has to apply in order to steer the coastal development toward a sustainable use of energy and resources. The following study areas have been considered (figure 1):

- (1) *Lagoon of Venice*, characterized by an extraordinary mix of activities: tourism, fishing, industry (petrochemical plants);
- (2) *Rimini*, one of the most important mass-tourism areas in the Mediterranean Sea;
- (3) *Conero* (Ancona), a mountain with a cliff coast, characterized by a *park* and a *marine protected area* with important ecosystems, and, in the northern part, by an important port (*Ancona*) and a petrochemical plant (at *Falconara*).

2. MATERIALS AND METHODS

The method developed is based on a conceptual model and follows a framework with several steps [Marotta et al., 2010]:

1. *Definition of homogeneous environmental management units, and analysis of spatial and temporal structure, hierarchy and dynamics over multiple scales.* For this purpose a habitat map based on landscape ecology was produced following the work of Naveh and Lieberman [1994], Brenner et al. [2006] and Marotta [2006]. A crucial first step here is to characterize seabed habitats accurately from geological and oceanographic data. The procedure adopted is based on the shelf classification applied in eastern Canada by Roff and Taylor [2000].

2. *Analysis of land-use changes in the coastal system.* In this step, landscape features and changes are identified in a temporal framework [Marotta and Mulazzani 2006].
3. *Implementation of spatial indices.* The spatial approach is the basis for analysis and planning [Babcock et al. 2005; Brenner et al. 2006] and for the assessment of indices for each patch type and state (a range of index's values is assigned to each type of patch). This method links land and sea use in the same framework [Marotta et al. 2010]. An urban and infrastructure index has been used as evaluation tool [Marotta 2004; Marotta et al. 2010].
4. *Conservation-gaps analysis.* IDRISI™ (Andes version) [Eastman 2006] is used in order to assess changes of habitats (land and sea) over time (from 1972 to 2001), to assess of ecosystem health, cumulative impacts and habitat loss in coastal ecotones [Thrush et al. 2008].
5. *Assessment of coastal conflicts.* For this purpose, and following the work of Vallega [1999], a coastal conflict index was used [Marotta 2004; 2006].
6. *MCA in order to minimize conflicts over a set of values and constraints.* The MCA, carried out with IDRISI, supports the representation of priorities distribution (*suitability maps*). These priorities are: i) industry and port development; ii) touristic development; iii) agriculture and/or aquiculture; iv) conservation of habitats and species.
7. *The evaluation of sea rise vulnerability and resilience* in order to assess the scenarios (data of sea level rise from Carraro, 2008).

In order to take into account the properties of the system this approach integrates both ecosystem health (*sensu* Jørgensen et al. [2005]) and landscape indices. Scenarios at 2015 are derived through the imposition of constraints in order to achieve the following objectives: conflict minimization, greenhouse gases (CO_{2e}) emissions reduction, ecological footprint lower than biocapacity. A fourth goal, habitat conservation and ecological network maximization, is not considered in this paper (see Marotta et al [2010]).

2.1 Data sets and system analysis

For the landscape analysis and identification, two Landsat satellite scenes are used for each study area. The data are then integrated with mapping data base Corine Land Cover 2000 (CLC2000), based on work by Perdigão and Annoni [1997] and EEA [2002]. Images are processed into landscape patch units; the classification is made by photo-interpretation and ground verification. Resulting data are used in order to calculate landscape metrics (fractal dimension and landscape diversity, for methods see Farina [2006], Eastman [2006]), and sustainability indicators and indices.

Data about environment, emergy, ecological footprint and socioeconomics are based on the following reports and data sets:

- *Lagoon of Venice:* data from Tiezzi [2004], Bastianoni et al. [2005] and Assessorato all'Ambiente del Comune di Venezia [2005];
- *Rimini:* data from Tiezzi and Marotta [2006];
- *Conero (Ancona):* data from Tiezzi and Marchettini [2002].

Data about vegetation ecology are based on Pignatti [1994]. Data about fauna are based on Casini and Gellini [2008], Bon et al. [2004] and Giacchini [2007]. Table 1 shows the sustainability indices and constraints used for the case studies. Data are calculated in a 5-km coastal fringe (4 km landward and 1 km seaward). The indices for system description and ecosystem health are the following ones.

Emergy is an index, introduced by Odum [1996], to take into account all the resources (natural and manufactured) sustaining a system. It is the quantity of solar

energy needed to obtain a product or an energy flow in a given process. Units are *solar emjoules (sej)*. Total emergy was subdivided into *renewable* and *non-renewable* emergy.

Empower is the emergy flow in time. Units are *sej* per time unit. *Empower density (ED)* is the ratio between total empower and surface area of the system (expressed in hectares or m²), a measure of the spatial concentration of emergy. The greater the ED, the more the area becomes a limiting factor for all future development. *Environmental loading ratio (ELR)* is the ratio between non-renewable (local and imported) emergy and renewable environmental emergy.

Carbon dioxide equivalent production is used to identify and quantify anthropogenic sources and sinks of greenhouse gases [Eggleston et al. 2006]. Units are tons of CO₂ eq / (person year). *CO₂ absorption* is calculated per each land use from the average vegetal biomass.

Ecological footprint (EF), developed by Wackernagel and Rees [1996], is a measure of the consumption of renewable natural resources by human population of a country, a region or the whole world [Wackernagel et al. 2006]. A population's EF is the amount of productive area required to sustain that population. The EF is a sustainability indicator, which provides a metric with a threshold (the biocapacity), that is a local carrying capacity. *Biocapacity*, or *available biological capacity (ABC)*, refers to the capacity of a given biologically productive area to generate an on-going supply of renewable resources and to absorb its spillover wastes. Un-sustainability occurs if the area's ecological footprint exceeds its biocapacity. *Ecological balance* (defined as ecological deficit if negative) is the difference between the EF of a population and the ABC in the space available for that population [Chambers et al. 2000; Wackernagel et al. 2006].

Landscape development intensity (LDI) is an index calculated from the non-renewable emergy per land use. Using land-use data and development-intensity measures (derived from energy use per area unit) LDI can be calculated for the coastal zones to estimate the potential impacts of human-dominated activities. LDI is used as an index of human disturbance gradient [Brown and Vivas 2005].

Ecosystem value is based on ecosystem services [Costanza et al. 1997], i.e. the benefits arising from nature or the ecological services associated with a particular benefit. They include ecological contributions to both market and nonmarket goods and services.

Human value is based on land prices. Land prices vary extremely from city to city and are highest in urban cores. The values used are average values per land/sea type.

Exergy (Ex) of a system is the maximum work possible during a process that brings the system to equilibrium with a heat reservoir. When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is then the energy that is available to be used. After system and surroundings reach equilibrium, the exergy is zero. *Eco-exergy* (or *ecosystem exergy*) is the chemical energy difference between the actual system and the thermodynamic equilibrium [Jørgensen et al. 2005].

Gross domestic product (GDP) is the total market value of all final goods and services produced in a country in a given year, equal to total consumer, investment and government spending, plus the value of exports, minus the value of imports.

Vallega [1999] defined *the coastal use interaction breakdown* as a square matrix where uses are indicated in rows and columns in the same order. Here the quantification of the index follows Grosskurth and Rotmans [2007] method, which develops a qualitative index (QSSI) taking into account time, scale and domain; here it has been modified in order to identify *conflicts* in the uses matrix.

2.2 Landscape indices

The conceptualization of a landscape described by patches of different land- and sea-use is made by the space transformation of indices in order to use them as a model.

Biological capacity potential or *biological territorial capacity (BTC)* is a measure of ecosystem functionality [Ingegnoli and Pignatti 2007] based on resistance stability,

vegetation type and metabolic data of vegetation. This synthetic function, referred to the main ecosystem, is able to compare landscape states by measuring the relative relation between respiration and gross production and between respiration and biomass. A more resilient and “healthier” ecotope has a higher BTC value than a more degraded one.

Percolation has found an interesting application in landscape ecology, and offers a method to describe and predict animal movement [Farina 2006]. A *critical probability* (p_c) = 0.593 marks the difference between two distinct cases: when the fluid remains in finite regions (percolation < p_c) and when the fluid crosses the lattice connecting every molecule of fluid with the others (percolation > p_c). Therefore, percolation can be considered a connectivity measure.

Fractal dimension and *landscape diversity* are calculated following Farina [2006]. *Natural habitat loss* is calculated as area loss from 1970, using satellite images.

The *Fluvial Functionality Index* (IFF) is a tool for an integrated assessment of rivers, and is largely applied in Italy [Siligardi et al., 2000]. The index was recently modified for the application to rivers in coastal and estuarine areas, as *RMFI* (*River Mouth Functionality Index*) [Vogli, 2010].

A *coastal, urban and infrastructural, sprawl index* (I_{sp}) was developed by Marotta et al., [2010], with the aim of understanding urban and infrastructural dynamics in coastal areas and to identify problematic areas. The assessment of I_{sp} at a macro scale is a good proxy of all human pressures on the coastal zone. Using CLC2000 terminology, I_{sp} represents the sum of the *natural* and *agriculture* patches (codes 2., 3., 4., 5.) changed into *urban and infrastructures* (codes 1.), over a given period of time.

2.3 Gap analysis and multicriteria analysis

Gap analysis and MCA of geographic information are carried out using IDRISI's *geographic resources analysis support-system*. The GAP processes is analyzed using IDRISI's *land change modeler* and according to Forman [1995]; results are published on Marotta et al., [2010].

3. RESULTS AND DISCUSSION

The dynamics of coastal areas, calculated using satellite images, show changes in a period of about 30 years. Corresponding values of sustainability/ecosystem-health indices and indicators for the studied areas are reported in Figure 1 and Table 1. The assessment of the later state (see Table 1) shows that:

- Coastal landscapes have a very low level of eco-health state in Rimini, where BTC is very low, LDI is very high, percolation in coastal zone (1 km) is lower than the threshold (0.59) and the footprint is 12 times higher than the threshold ($ABC=0.91$).
- GDP per surface unit in Venice is lower than in other areas because also the surface of the lagoon (where there are few economic activities and no inhabitants) is considered.

	Venice lagoon	Rimini province	Conero area	Error
Non renewable Energy (sej/yr) per ha	9.3E+16	5.5E+16	7.3E+16	20%
Renewable Energy (sej/yr) per ha	2.6E+11	1.0E+10	1.0E+10	20%
Non renewable Energy for coastal protection (sej/year)	1,87E+19	1,23E+18	5,50E+17	20%
LDI ¹	4.86*	7.12*	3.95*	30%
CO ₂ absorption (ton) per ha	3.8E+03	1.3E+03	3.6E+03	20%
Greenhouse gas emissions (ton per person per year)	14.4	7.2	7.9	20%
Ecological Balance (ABC - EF)	-3.23	-6.94	-4.04	20%

Exergy (J) per ha	5.8E+09	1.9E+09	6.0E+09	20%
Ecosystem value (euro) per ha	3.4E+03	0.9E+03	1.9E+03	10%
Human Value (euro) per ha	5.0E+05	7.9E+05	6.6E+05	30%
Coastal use conflicts¹	0.85	0.41	0.53	5%
BTC (J/yr) per ha	3.8E+10	0.9E+10	3.6E+10	15%
Percolation (in total area)	0.93	0.86	0.91	5%
Percolation in coastal area (5km)	0.71	0.41	0.89	5%
Percolation in coastal area (1km)	0.68	0.35	0.68	5%
Fractal dimension	1,72	1,19	1,56	10%
Landscape diversity (normalized to 1)	0,91	0,11	0,86	(10%)
Natural habitat loss in total area, period 1970-2001* (ha) {total area, in ha}	2.29E+3 {2.50E+5}	4.11E+3 {1.60E+5}	18.7E+3 {1.23E+5}	5%
Average Status of Rivers in the coastal zone (IFF or RMFI**)	Score 101-120 Level III/IV Status fair-poor	Score 121-180 Level III Status fair	Score 180-210 Level II/III Status good-fair	10%
GDP (total per year, 2004), euro/ha	0.9E+5	1.8E+5	7.2E+5	10%
Emergy for coastal protection (sej/year)	4,34E+23	7,15E+22	3,43E+22	20%
Coastal Urban and Infrastructure in total area Sprawl Index (1970-2001*)¹	7.8	7.5	7.6	10%

Table 1. Coastal sustainability indices and constraints for the case studies. Data are calculated in the 5 km of coastal fringe (4km landward and 1km seaward, for Venice lagoon is calculated whit the entire Lagoon and 4 km Landward and 1 km seaward). ¹LDI, Coastal Urban and Infrastructure in total area Sprawl Index (1970-2001*) and Coastal use conflicts have not unit of measures. * First year of analysis for Venice is 1972, for Rimini is 1975, for the Conero area is 1976.**Methodological sources: APAT [2007], Vogli [2010].

- In the Conero area the highest net habitat loss is found, even though the state of landscapes eco-health (BTC, percolation) is good.
- The total fluxes of emergy in the Venice case show the importance of the lagoon in natural fluxes: higher levels of emergy are partly due to the importance of estuarine-lagoon processes in the coastal area. This is consistent with the higher level of non-renewable emergy in the Venice lagoon with respect to the other areas.
- The lower level of empower density in the Conero area reflects the lower use of energy and a lower flux of materials in this area.
- The high environmental loading ratios in Venice lagoon and Rimini, which are higher than the average value for Italy (60.32), as shown in Sweeney et al. [2007], reflect the higher fluxes of non-renewable emergy per person (from both local and non-local energy and materials input).

3.1 MCA and decision-support scenarios

The general principles used to derive scenarios of effective environmental policies and management strategies are based on an ecosystem approach, as described by Gaydos et al. [2009]. The index developed takes into account these principles because: (1) the area is landscape shaped; (2) percolation is a connectivity measure; (3) gap reduction is a fragmentation minimization; (4) BTC is a measure of ecosystem integrity and resilience; (5) emergetic, economic and ecological values are taken into account.

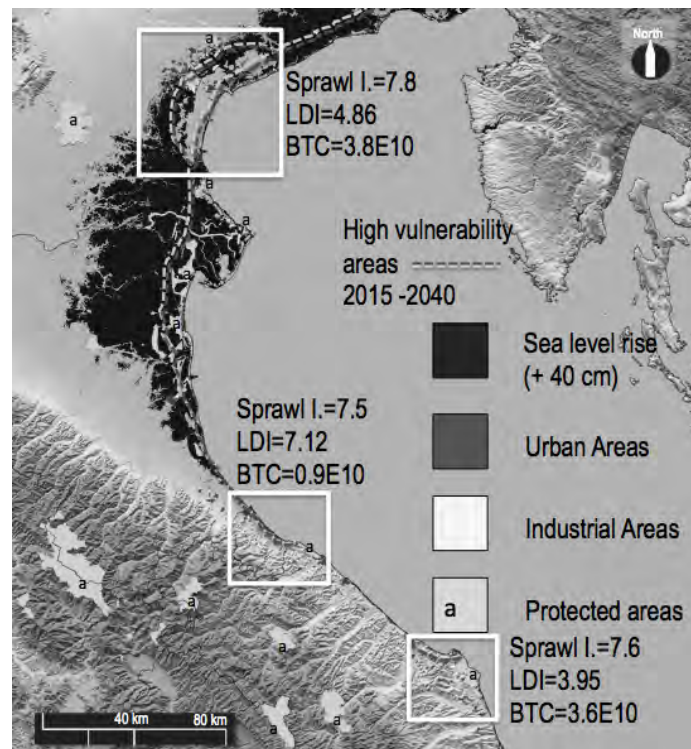


Figure 2. Study areas from north to south: Venice Lagoon, Rimini Province, Conero Area (Ancona Province), sprawl index, LDI and sea level rise as an indicator of the coastal vulnerability state.

The main objectives of the suitability maps used in the MCA are: minimizing conflicts and minimize ecological footprint. Different objectives can be maximized: industry and port development; touristic development; agriculture and/or aquaculture; conservation of habitats and species. For each objective, a suitability map is created, as the first step of the MCA, using the land-use and patch data as criteria [Marotta et al., 2010]. Once the multicriteria suitability maps have been created for each objective, a multi-objective scenario is obtained for each area (assigning a weight to each objective) and the threshold are imposed in order to minimize the ecological footprint and the greenhouse gas production.

Scenarios are characterized by the parameters presented in Table 2.

In the Conero scenario, a policy of 70% reduction in nonrenewable energy consumption, 80% increase in waste recycling, and 70% shift from private transport to public transport (trains and electric buses) is needed to reach an ecological footprint of 2.1 ha per person per year, considering an increase of population around 1% per year (as per current trends).

In the Rimini scenario, a policy of 80% reduction in nonrenewable energy consumption, 90% increase in waste recycling, and 90% shift from private transport to public transport (trains and electric buses) is needed to reach an ecological footprint of 1.0 ha per person per year, considering an increase of population around 2% per year (as per current trends). In this case, a policy for an increase of biocapacity is needed, too.

In the Venice scenario, a policy of 60% reduction in nonrenewable energy consumption, 78% increase in waste recycling, and 70% shift from private transport to public transport (trains, boats and electric buses) is needed to reach an ecological footprint of 1.8 ha per person per year, considering no increase of population (as per current trends).

Scenario at 2015	Venice lagoon	Rimini province	Conero area	Error
Ecological footprint (global hectares) (at the actual level of consumption)	7.2	7.9	6.6	20%
Biocapacity (global hectares)	1.8	0.91	2.1	20%
Gap, unprotected areas	0	0	0	5%
Coastal Urban and Infrastructure Sprawl Index	3.2	3.1	3.1	20%
Coastal use conflicts	0.10	0.10	0.10	5%
Greenhouse gas production (tonnCO_{2eq} per inhabitant per year)	3.5	3.0	2.9	20%
Non renewable emery for coastal protection (sej/year)	1,92E+18	1,53E+17	7,53E+16	20%
Coastal use conflicts	0.10	0.10	0.10	5%

Table 2. Table of Results for final decision scenario.

In all the cases studied, the non renewable emery intensity for coastal protection activities is growing during time, then the socio-ecological system resilience is decreasing. Only a new design and management for coastal landscape can change this disequilibrium.

4. CONCLUSIONS

In this paper an index and a methodology for integrated coastal zone management for a suitable “way down” have been presented.

The key issues are:

- A. integration of both health (systemic) and landscape/seascape (spatial) indices;
- B. the evolutionary/historic approach (*i.e* the system evolution during 30 years);
- C. the imposition of the ecological thresholds as planning objectives.

Sustainability of Rimini and Venice coastal zone will not be achieved in the short term. The lagoon of Venice mitigates many anthropogenic impacts, coming from the inland area and the port, and from fishing and touristic activities, so it is important to protect and restore it. The Rimini area presents high ecological footprint, high landscape development intensity and low biocapacity, together with a critical value of percolation (connectivity among habitats). The Conero area can reach a sustainability level through the protection of natural coastal space from potential sources of anthropogenic impacts. A more integrated social change and an improvement in landscape health is the only solution to increase the resilience (*sensu* Gunderson *et al.*, 2009] of socio-ecological systems.

REFERENCES

- APAT (2007). IFF 2007. *Indice di Funzionalità Fluviale. Nuova versione del metodo revisionata e aggiornata*. Agenzia Nazionale per la Protezione dell'Ambiente e per i Servizi Tecnici, Roma, 325 p.
- Assessorato all'Ambiente del Comune di Venezia (2005) *Speciale Ambiente Venezia, Rendiconto 2001/2005*. Comune di Venezia, Venezia, 219 pp.
- Babcock EA, Pikitch K, McAllister MK, Apostolaki P, Santora C (2005) “A perspective on the use of spatialized indicators for ecosystem-based fishery management through spatial zoning”. *J Mar Sci* 62: 469-476.
- Bastianoni S, Marchettini N, Niccolucci V, Pulselli FM (2005) “Environmental accounting for the lagoon of Venice and the case of fishing” *Ann Chem (Rome)* 95: 143-152.

- Bon M, Semenzato M, Scarton F, Fracasso G, Mezzavilla F (2004) *Atlante faunistico della provincia di Venezia*. Provincia di Venezia, Venezia, 260 pp.
- Brenner J, Jimenez J Sarda R (2006) "Definition of Homogeneous Environmental Management Units for the Catalan Coast." *Environ Manag* 38: 993-1005.
- Brown MT, Vivas MB (2005) "Landscape Development Intensity Index". *Environ Monit Assess* 101: 289-309.
- Carraro C (Ed.)(2008). *Cambiamenti climatici e strategie di adattamento in Italia. Una valutazione Economica*, IL Mulino, Bologna, 518 p.
- Casini L, Gellini S (2008) *Atlante dei vertebrati tetrapodi della provincia di Rimini*. Provincia di Rimini, Rimini, 512 p.
- CBD (2000). *Decision V/6, Conference of the parties*. Nairobi 15- 26 May, 2000 Available: <http://www.cbd.int/decisions/?lg=0&m=cop-05&d=06> [last accessed 2/25/2008].
- Chambers N, Simmons C, Wackernagel M (2000) *Sharing Nature's Interest, Ecological footprints as an indicator of sustainability*. Earthscan, London.
- COM/2000/547 *Communication by the Commission to the Council and the Parliament on Integrated Coastal Zone Management: a Strategy for Europe*, adopted 27 September, 2000.
- COM(2005) 504 and 505 *Thematic Strategy on the Protection and the Conservation of the Marine Environment, including a proposed Marine Strategy Directive*, 14.10.2005.
- COM/2007/0308 *Communication from the Commission - Report to the European Parliament and the Council: an evaluation of Integrated Coastal Zone Management (ICZM) in Europe*.
- Costanza R, D'arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill R V, Paruelo J, Raskin R G, Sutton P van den Belt M (1997) "The value of the world's ecosystem services and natural capital". *Nature* 387: 253-260.
- DEFRA 2006. *Marine Spatial Planning Pilot*, final report, MSSP Consortium. Available: http://www.defra.gov.uk/science/Project_Data/DocumentLibrary/ME1407/ME1407_32_96_FRP.pdf Accessed 2/20/2008.
- Eastman JR (2006) *IDRISI Andes. Guide to GIS and Image processing*. Clark University, Worcester, 327 p.
- EEA (European Environment Agency) (2002) *CORINE Land Cover update, I&CLC2000 project, Technical Guidelines*. http://www.eea.europa.eu/publications/technical_report_2002_89. Accessed 4 May 2010
- Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K (2006) *IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, Hayama, Kanagawa, Japan.
- Encora network 2008. *European platform for coastal research coordination actions. Activities Theme 3: coastal and marine spatial planning* Available:<http://www.enpl.gr/encora/index.php>
- Farina A (2006) *Principles and Methods in Landscape Ecology. Towards a Science of Landscape*. Springer-Verlag, New York, 448 pp.
- Farinelli F (2003) *Geografia. Un'introduzione ai modelli del mondo*. Einaudi, Torino, 232 pp.
- Forman RTT (1995) "Some general principles of landscape and regional ecology". *Landsc Ecol* 10: 133-142.
- Gaydos JKL, Dierauf G, Kirby D, Brosnan K, Gilardi G, Davis E (2009) "Top 10 Principles for designing healthy coastal ecosystems like the Salish Sea". *EcoHealth* 5: 460-471.
- Giacchini P (2007) *Atlante degli uccelli nidificanti della provincia di Ancona*. Provincia di Ancona, Ancona, 346 p.
- Grosskurth J, Rotmans J (2007) "Qualitative System Sustainability Index: A new type of sustainability indicator". In: Hák T, Moldan B, Dahl AL (eds) *Sustainability indicators. A Scientific Assessment*. Island Press, London, pp 177-187.
- Gunderson, L, and Holling C S (Eds.), (2002). *Panarchy: understanding transformations in human and natural systems*. Island Press, Washington, 450p.
- Gunderson, L H, Allen C R, C S Holling, (Eds.) (2009). *Foundations of Ecological Resilience*, Island Press, Washington, 496 p.
- Ingegnoli V, Pignatti S (2007) "The impact of the widened landscape ecology on vegetation science: towards the new paradigm" *Rendiconti Lincei* 18: 89-122.
- Jørgensen S.E., F.L. Xu, F. Salas, and J. Marques, 2005. "Application of Indicators for Assessment of Ecosystem Health," in S.E Jørgensen., R. Costanza and F.L. Xu (eds), 2005. *Handbook of Ecological Indicators for Assessment of Ecosystem Health*, CRC Press, Boca Raton, pp. 5-104.
- Marotta L (2004) "Ecologia Urbana e sistemi costieri". In: Bettini V (ed) *Ecologia urbana*. UTET, Torino, pp. 419-454.

- Marotta L (2006) "Unità di paesaggio in Laguna". In: Guerzoni S, Tagliapietra D (eds) *Atlante della Laguna. Venezia tra terra e mare*. Marsilio editore, Venezia, pp. 200-201.
- Marotta L, Mulazzani A (2006) "Indici di percolazione e funzionalità del paesaggio di Torre Flavia". In: Battisti C (ed) *Biodiversità, gestione, conservazione di un'area umida del litorale tirrenico: la Palude di Torre Flavia*. Gangemi editore, Palermo, pp 130 -141.
- Marotta L, Ceccaroni L, Matteucci G, Rossini P, Guerzoni S (2010). "A decision-support system in ICZM for protecting the ecosystems: integration with the habitat directive", *J Coast Conserv*, DOI 10.1007/s11852-010-0106-3.
- Meiner A (2009) "Integrated maritime policy for the European Union — consolidating coastal and marine information to support maritime spatial planning". *J Coast Conserv* doi:10.1007/s11852-009-0077-4.
- Munda G (2004) "Social multi-criteria evaluation: Methodological foundations and operational consequences". *Eur J Oper Res* 158:662–677.
- Naveh Z, Lieberman AS (1994) *Landscape Ecology. Theory and Applications*, 2nd edn. Springer, New York, 360 p.
- Odum HT (1996) *Environmental accounting: Energy and environmental decision making*. Wiley & Sons, New York, 370 p.
- Ortolano L (1997) *Environmental Regulation and Impact Assessment*. Wiley & Sons, New York, pp 620
- Perdigão V, Annoni A (1997) *Technical and methodological guide for updating the CORINE land cover database*. EUR 17288 EN, ECSC-EC-EAEC, Brussels. <http://www.ec-gis.org/docs/F27057/CORINE.pdf>. Accessed 2/4/2010.
- Pignatti S (1994) *Ecologia del Paesaggio*. UTET, Torino, 230 p.
- Roff JC, Taylor ME (2000) "National frameworks for marine conservation – a hierarchical geophysical approach". *Aquat Conserv: Mar Freshw Ecosyst* 10:209-223.
- Soncini Sessa R (2004) *MODSS Per decisioni integrate e partecipate*. Mc Graw-Hill, Milano, 512 p.
- Sweeney S, Cohen M, King D, Brown M (2007) "Creation of a Global Emergy Database for Standardized National Emergy Synthesis". In: Brown MT, Bardi E, Campbell DE, Comar V, Huang S, Rydberg T, Tilley D, Ulgiati S *Emergy Synthesis 4: Theory and applications of the emergy methodology. Proceedings of the 4th Biennial Emergy Conference*. Center for Environmental Policy, University of Florida, Gainesville pp 483-497.
- Thrush SF, Halliday J, Hevit JE, Lohrer AM (2008) "The effects of habitat loss, fragmentation, and community homogenization on resilience, in estuaries". *Ecol Appl* 18 (1):12–21.
- Tiezzi E, Marchettini N (2002) *Analisi di sostenibilità della Provincia di Ancona*. Provincia di Ancona, Assessorato all'Ambiente, Ancona, p 204.
- Tiezzi E (2004) *Analisi di Sostenibilità della Provincia di Venezia*, Provincia di Venezia, Internal Report. <http://politicheambientali.provincia.venezia.it/ecm/faces/public/politicheambientali>. Accessed 12 October 2007.
- Tiezzi E, Marotta L (2006) *Analisi di sostenibilità della Provincia di Rimini*. Provincia di Rimini, Rimini, pp 45
- Vallega A (1999) *Fundamental of coastal zone management*. Kluwer, Dordrecht, pp 263
- Van Kouwen F, Dieperink C, Schot P, Wassen M (2008) "Applicability of decision support systems for integrated coastal zone management". *Coast Manag* 36:19 -34.
- Vogli L (2010) *Analisi delle foci e dei tratti terminali di corsi fluviali attraverso indici calcolati su differenti scale spaziali e temporali*. Tesi di laurea, Università degli Studi di Bologna, Anno Accademico 2008-2009, 290 p.
- Wackernagel M, Rees WE (1996) *Our Ecological Footprint: Reducing Human Impact on the Earth*. New Society, Gabriola Island, pp 176.
- Wackernagel M, Moran D, White S, Murray M (2006) "Ecological Footprint accounts for advancing sustainability: measuring human demands on nature", in P. Lawn, *Sustainable Development Indicators in Ecological Economics*. Edward Elgar, Cheltenham, pp 246–267.

DEFOSSILIZATION: LINKING ENERGY CONSUMPTION AND RENEWABLE GENERATION

*Angel A. Bayod-Rújula*¹, Amaya Martínez*

CIRCE - Universidad de Zaragoza, Spain

ABSTRACT

The expected increasing levels of energy consumption in the whole world will lead to depletion of natural resources and the consequent environmental damage. In the light of the difficulties, efforts must be aimed to reduce the individual and collective demands, and a fast transition to renewable energies is needed. An energy structure based on renewable resources must be accompanied by a reduction in the consumption by energy efficiency efforts, and by using the appropriate energy form to produce energy services. Additionally, the costs of solar and wind power systems have dropped substantially in the past 30 years, and continue to decline, while the prices of oil and gas significantly fluctuate.

Then, the two pillars of our future energy policy are energy conservation and renewable energies. Some policies suggested in literature are to educate objectively and effectively, improve information and labelling; and expand the obligation to supply and buy energy from renewable resources.

In this paper, the *Consumption-linked to-Renewable energies* mechanism (CLR), claiming for every new unit of consumption to be associated to a new renewable generation, is presented. When a consumer decides to buy any equipment, the total consumption is evaluated and a clean generation unit must be acquired at the same time. Along these lines, conscious of the importance of their consumptions, and due to the economic impact, consumers will tend to use efficient technologies that allow their high levels of well-fare (consumption and economy) compatible with energy conservation.

A case study, an electric car with its complementary photovoltaic system, where defossilization is achieved with cost-effective measures is presented. With a moderate size PV system we would get electricity not only for that vehicle, but also for the energy consumed in the production of the car and the PV system itself and some extra electricity for other uses.

Keywords: energy degrowth, defossilization, consumption linked to renewable energies (CLR) mechanism, CLR mechanism

1. INTRODUCTION

Energy demand has been continuously growing with high rates for the last decades. In particular, a new increase in electrical demand during the first half of this century is expected.

The global population on the Earth by 2050 is estimated to reach 9.000 million people (UN, 2002). Even today, a great part of the population is deprived of elementary services such as electrification and fresh water supply (UN, 2006). Additionally, clean drinking water is one of the most important international issues today due to rapidly increasing population and the economic growth.

Although water management strategies, water saving measures and water reuse and reclaim are clearly the first alternatives, desalination has been relied on to provide fresh water for large cities and countries across the world (ESCWA, 2001a). But current desalination technologies (either membrane or thermal) require large amounts of energy. In the oil rich Middle East region, desalination satisfies close to 50% of the domestic and industrial water requirements (ESCWA, 2001b). There desalination

* Corresponding author: E-mail: aabayod@unizar.es; Phone: +34 976 76 19 20

plants are typically driven by oil or its associated gas. Desalination based on fossil fuels is neither sustainable nor economically feasible in a long-term perspective, as fuels are increasingly becoming expensive and scarce and contribute to the generation of greenhouse gases in addition to various pollutants and particulate matter. Then, environmental protection through the use of renewable energy must become part of the present and future desalination industry (Valero et al., 2001; Fritzmann et al., 2007; Gabbrielli, 2008; Bayod and Martínez, 2008).

On the other hand, mobility is a major driver of economic growth and societal development. A large share of mobility relies on passenger car use – and the use of the passenger car is expected to continue to increase further, especially in developing and emerging countries. Today, transport is almost exclusively dominated by internal combustion vehicles – with approximately 95 % of transport reliant upon liquid carbon fuels derived from crude oil (Rodrigue, 2009). There is no other sector which shows such a high level of dependence on one single source of primary energy.

2. ENVIRONMENTAL ASPECTS

Environmental damage is largely linked to the increasing use of *energy*. The electric power sector is one of the major industries using fossil fuels to generate electricity (Akella et al., 2009). As it is well known, generation and consumption of energy represents more than 80% of greenhouse gas emissions in the European Union, over 77% of emissions of substances that contribute to tropospheric ozone formation, 66% of the substances that cause acid rain, 81% of particulate emissions and emissions of heavy metals (EEA, 2008). The impact also includes the generation of waste throughout the cycle of extraction, processing and consumption, toxic waste, water consumption, sometimes irreversible degradation of ecosystems, noise and deterioration of scenery.

Transport is responsible for more than a fifth of the EU's greenhouse gas emissions and it is the only sector with growing emissions. Between 1990 and 2006, greenhouse gas (GHG) emissions from overall transport (including international aviation and marine) in EU-27 have much increased (+35.8%) while emissions from non transport sectors have decreased (-13.4%) over the same period. Road transport is, in turn, the largest contributor to carbon dioxide emissions (93 % in 2007). Transport is also a rapidly growing source of N₂O emissions (89 % between 1990 and 2007). Besides, international aviation and marine have shown the fastest growth over the same period (+73%), and weighted 23.5% of overall transport emissions in 2006 (EEA, 2010). Clearly, the transport sector is being run by fossil fuels. Since the stored fossil resources in our planet are finite, the current rate of consumption is leading to the depletion of those resources. During millenniums the energy has been accumulated and in some centuries we could burn it to smoke. From the previous figures, it is clear that its use impacts negatively the environment. Moreover, risk and problems of security of supply and geopolitical stress may arise.

3. ACTIONS TO BE IMPLEMENTED

Thinking about the actions to be launched, the first effort must be, obviously, aimed to reduce the individual and collective demands. More efficient measures should be immediately taken in consumption and transmission, distribution and generation systems. Besides education in the importance of the limitation of use of limited resources and the need of social equity, a better use of these energies is a must. Education is perhaps the more powerful weapon to combat the rebound effect.

Then, together with the imperative energy efficiency, the two pillars of our future energy policy are energy conservation and renewable energies.

3.1 Efficient consumption and energy conservation

We can not just passively wait for the total depletion of resources. Becoming independent from the current main source of energy, the non-renewable sources, is imperative. Nowadays, there exist cost-effective technologies that allow us to maintain an energy saving activity levels and wellbeing; and new research fields are opened.

Demand side management, efficiency improvements, and electric load reductions are important factors to address. On the other hand, consumption patterns should shift towards the demand for ecological and socially benign products. Assessing consumer behaviour is a crucial prerequisite for changing our energy system to sustainability and for renewable resources being able to contribute a large part of the national and global energy demand.

Experiments with electricity customers indicated that consumers are indeed quite responsive to conservation incentives and disincentives (Edinger and Kaul, 2000). There is a vast energy saving potential through setting up incentives for consumers to use their energy efficiently.

Load management must be the first step in reorganizing the energy system, and it always is the most cost-effective alternative to cut down the load side first before investing in renewable technologies.

The efficiency of appliances to convert electricity into energy services is increasing steadily, and still has improvement potential. For instance, lighting is responsible for 14% of EU electricity consumption. Lighting with more efficient lamps is an activity that permits directly the reduction of the demand. Modern lighting solutions are 50-100 times more efficient than candles. In the same way, with current technology, over 80% savings in lighting can be achieved, and the lamps can last even 15 times longer than the standard equivalent. Energy use for individual lighting applications can be reduced by a factor 5 or more: dimmable lighting systems, ensuring exactly the right amount of light in the right place at the right time.

Improvements in electrical motors, in more efficient transformers, distribution systems, or in control systems are other examples. In motor driven systems (pumps, compressors, fans, washing machines, electric trains), it is possible to reduce losses by 30% on average. Distribution transformers, one of the most efficient machines ever designed by man, can still reduce losses through the use of amorphous iron.

In the generation of electricity, the very efficient systems of cogeneration and tri-generation plants are successfully installed in hospitals, hotels and office buildings. If those buildings are located in water scarce areas and near the sea, the possibility of including desalted fresh water in the multi-purpose generation process is highly attractive. Therefore, electricity, heat, cold and fresh water can be produced simultaneously in a decentralized form.

Losses in refrigeration have been reduced historically by a factor 5, from the levels at the end of the 80's to the best available technology in class A+ appliances.

Modern high temperature heating solutions for industrial processes can in some cases save up to 80% of primary energy and up to 60% of CO₂ emissions through their efficient use of primary energy. With heating controls for building energy management, ensuring buildings are only heated when needed.

The use of high speed electric trains instead of air transport reduces primary energy use per passenger and km by a factor 3 and CO₂ emissions by a factor 4. For example, an electric vehicle can be about 4 times as efficient in converting primary energy into transport services (Eurelectric, 2004).

Using electric trains instead of diesel trains reduces CO₂ emissions by a factor 4 and primary energy use by a factor 2. Electric vehicles are more efficient as vehicles with internal combustion engines.

Efficient heat pumps, drawing heat from the underground require 20-40 kWh of electricity to supply 100 kWh of heat; they typically reduce final energy demand for heating by at least a factor 3 and primary energy demand by at least 25%. With

induction heaters for cooking, 90% of (final) energy goes in the pan, compared to 55% for gas-fired cooking.

The electric car offers significant environmental benefits, especially in urban areas. Electric vehicles have zero tailpipe emissions, but there are, of course, emissions involved in the production of electricity. One major benefit of electric vehicles is the "displacement" of harmful air pollutants from urban to rural areas, where population exposure is lower. Noise levels are also lower, particularly in urban driving conditions.

Another major advantage of electric vehicles is their energy efficiency. With a tank-to-wheel efficiency in the range of 60 to 80 %, they outperform conventional cars four-fold. Generally, electric vehicles show greatest energy savings at low speeds and in situations involving frequently-changing driving dynamics, which is another reason why cities are a prime target market.

Electric vehicles will only have a positive impact on the environment if they replace a significant amount of the mileage driven in conventional cars. An increasing defossilization of the transport sector is essential. The main problem is that the successful market introduction of vehicles with electric driving mode is highly dependent on the availability of a battery technology that allows reliable on-board storage of electric energy.

The energy demand of battery production is assumed to be significant, although the quantification of environmental impacts of battery production, recycling and disposal have not been investigated in greater detail as battery technology is still under research and no data on the final composition of automotive batteries is available.

On the other hand, energy storage has a very important strategic value in future electricity networks. It can allow the reduction of spinning reserves to meet peak power demands, by storing electricity, heat and cold, which is produced at times of low demand and low generation, and releasing it when energy is most needed and expensive.

The low cost of power generated by fossil fuel plants has made this inefficient use of energy economically cost-effective. Efficient integration of this distributed generation requires network innovations. A development of active distribution network management, from centralised to more distributed system management is needed. Information, communication, control infrastructures will be needed with increasing complexity of system management (Bayod, 2009).

On site production reduces the amount of power that must be transmitted from centralised plant, and avoids resulting transmission losses and distribution losses as well as the transmission and distribution costs, a significant part (above 30%) of the total electricity cost, due to the fact that generation buses and consumption are closer.

3.2 Defossilization

The adoption of more efficient energy use patterns and techniques can perhaps help us to reduce overall demand but we will still need to find new supplies of energy. The low cost of power generated by fossil fuel plants has made this inefficient use of energy economically cost-effective.

We need to sustain fossil-based industries for their industrial applications, rather than as primary sources of energy. Oil is used for lubricants, dyes, plastics and synthetic rubber. Coal products are used to make creosote oil, benzene, toluene, ammonium nitrate, soap, aspirin and solvents. Natural gas is an important desiccant in industry and it is used in ammonia, glass and plastic production (Abbott, 2009). But conventional energy sources based on oil, coal, and natural gas are damaging economic progress, environment and human life. Renewable systems convert free resources in electricity, with a wide social support, without using fossil energies (defossilization).

Renewable energy technologies rely on the use of natural energy resources such as solar radiation, the winds, waves and tides, which are, by definition, naturally replenished. From them, we can obtain both electricity and heat. Fortunately, the renewable resource potential is large, and the economics of the conversion technologies are beginning to look reasonable (Evans et al., 2009). Almost every area on the Earth receives enough energy for its development. Solar energy potential alone has been found to exceed the total world energy demand by several orders of magnitude (the theoretical solar potential is 3,900,000 exajoules per year, some 7.000 times greater than the global primary energy demand). Wind has an important potential too.

In the renewable energy systems, every kWh invested in their construction, operation and maintenance, considering even the recycling and restoration processes is returned multiplied by 10, 15, 20, -the so called Energy Return Factors, or EROIs-without harmful environmental consequences. Technical efficiencies and economic cost-effectiveness of modern small-scale renewable power generation technologies have improved impressively over the last decades.

Photovoltaics and Solar thermal power are relatively new technologies which have already shown enormous promise. The environmental benefits of their use are the reduction of impacts (air pollution, lower greenhouse gas emissions, lower impacts on watersheds, reduced transportation of energy resource and maintenance of natural resources for the long term (Jefferson, 2008)).

Both distributed rural and centralised urban demand can be covered by renewable energy technologies. The decentralized characteristics of solar energies may play a significant role for power supply in rural areas where grid electricity is not available and in centralised urban demands as well. PV and CSP plants can be used exclusively for power generation in grid connected installations and contribute to the reduction of the consumption of fossil fuels.

Distributed solar generation technologies in many cases provide flexibility because of their small sizes and the short construction lead times compared to most types of larger central power plants. If besides electrical power it is necessary to satisfy drinking water demands, the combination of these systems with desalination methods offers very attractive and efficient solutions. With few environmental impacts and a massive resource, solar energy offers a great opportunity to the sunniest countries.

Although still more expensive than fossil fuel generation, renewable energies show advantages due to their modular character and their ability to add new capacity incrementally and adjustably to the current energy demand. From an investment point of view it is generally easier to find sites for Renewable Energy Systems (RES) than for a large central power plant and such units can be brought online much more quickly. Capital exposure and risk is reduced and unnecessary capital expenditure avoided by matching capacity increase with local demand growth.

As PV prices declined rapidly, photovoltaic became an option for powering residential housing located off the grid and are today at the turning point of becoming cost-effective even for grid- connected applications

Roofs present a large potential of suitable areas for installation of photovoltaic (PV) plants. Flat roof PV installations have the advantage of being able to be optimally positioned with support structures, and the inclination angle can be adjusted. Building-integrated systems offer cost reductions in both energy and economic terms over centralised PV plants, especially if the costs of avoided building materials are taken into account. Other important aspect is locality, i.e. improved utilization of local resources. Distributed energy generation may also promote local business opportunities, and develop products and services based on local raw materials and labour. This, in turn, causes a need for high quality education.

3.3 Linking consumption to Renewables: the CLR mechanism

The global energy demand is expected to grow. An energy system based on renewable resources is not feasible without reducing the consumer load side by energy efficiency efforts and by using the appropriate energy form to produce energy services. The question that arises is not how to meet today's electricity demand with renewable technologies, but how to adapt our energy demand to a feasible amount of power that could be provided by renewable resources. Public support is growing for renewable technologies. Public opinion polls have shown a preference for energy conservation, energy efficiency, and renewable energy resources. There are a significant number of customers who are even willing to pay higher prices for clean energies, although the restructuring debate has often leaned in the direction of how to decrease prices.

On the other hand, the costs of solar and wind power systems have dropped substantially in the past 30 years, and continue to decline, while the price of oil and gas continue to fluctuate.

In the following, a new mechanism is presented. By the Consumption-linked to-Renewables mechanism (CLR), every new unit of consumption must be accompanied by a new renewable generation. When a consumer decides to buy any equipment or appliance, the total consumption must be evaluated and a clean generation unit must be acquired at the same time. Acting that way, consumers are conscious of the quantity and importance of their consumptions and the obligation of cancelling them. As they must invest in new renewable generation systems, they contribute to the health of the planet instead of worsen the situation, and they can feel better for that. And, due to the economic impact of their consumption, they will tend to use efficient technologies that allow their high levels of well-fare compatible with energy conservation.

4. CASE STUDY: LINKING AN ELECTRIC CAR TO A NEW PHOTOVOLTAICS SYSTEM

In this section, an example of application of the CLR mechanism is presented. Let us suppose we need to buy a new car. We can choose to buy an electric car or a conventional car. The Spanish government is committed to have one million electric or hybrid cars on the Spanish roads by 2014.

An average annual passenger car travels a distance of about 20,000 km per year, and the energy cost of driving an electric car can be settled as 0.16 kWh/ km. The annual energy cost would therefore be of some 3,200 kWh/year. The energy cost of a conventional car fuelled by gasoline is 0.6 kWh/km, i.e., 3.75 times more.

Looking for a comprehensive analysis, the energy required in the construction of the car has also to be considered. It takes about 20.000 kWh (73 GJ) of energy to manufacture a vehicle (Nada, 2006). This is less than 10% of the total lifecycle energy consumption of a conventional vehicle, but with the lower consumption of an electrical vehicle, this quantity is above 50% of the total lifecycle energy consumption.

With the Consumption-linked to-Renewable energies mechanism (CLR), every new unit of consumption must be associated to a new renewable generation. We could associate then the purchase of this new car to the installation of a new renewable generation systems.

In this case study, we associate the new car to a new photovoltaic (PV) system. Solar power offers a sustainable alternative to fossil fuels for electricity production. Solar energy potential alone has been found to exceed the total world energy demand by several orders of magnitude. The theoretical solar potential is 3,900,000 exajoules per year, some 7.000 times greater than the global primary energy demand.

Photovoltaic (PV) effect is the direct conversion of sunlight radiation into electricity. Photovoltaic technology is modular, with a long lifetime (guarantees given by manufacturers ensure that in 25 years the peak power decrease is moderated). It is silent and it present good environmental characteristics. Photovoltaic systems are

called to play a fundamental role in the embedded generation of electricity from renewable sources because they present several advantages such as high reliability, low maintenance requirements, simple structure, low transportation cost and short construction time. The continuous development and advances in the PV sector facilitates new solutions for the solar radiation conversion, giving rise to less costly production rates. This reduction of prices together with the rising price of electricity is expected to contribute to the equivalence of prices between the electricity produced on PV installations and with the mix of sources currently present in the electricity systems, i.e., the grid-parity.

Roofs and façades present a large potential of suitable areas for installation of PV plants. The advantages of using surfaces of a building for the installation of photovoltaic systems for the distributed generation of clean energy are widely recognized.

In order to analyse the energy performance of a PV plant it is necessary to establish the irradiation level and some climatic conditions. In absence of real measurements, the available solar potential and climatic parameters can be evaluated from data bases.

In this study, the analysis of the electric generation of the PV systems was elaborated using a simulation program (PVSYST) that computes the hourly production. Commercial crystalline Si PV modules have been used in the simulations.

In order to consider the differences with latitude, three locations in Europe with different solar irradiation and temperatures are studied. The selected locations are Zaragoza in Central Spain, Cádiz (in South Spain) and Berlin (Germany).

The Final system yield Y_f (the ratio that expresses the energy produced per year by the unit of peak power installed, and it helps to determine the solutions with highest specific productivity annual) in Zaragoza is 1,258 kWh/kWp

It is of high interest to study not only the annual PV system electrical production but also some energy parameters as the Energy Payback Time (EPBT) or the Energy Return Factor (ERF). EPBT is defined as the ratio of the total energy input during the system life cycle and the yearly energy generation during system operation. ERF is defined as the ratio of the total energy generation during the system operation lifetime and the total energy input during the system life cycle. The parameters EPBT and ERF indicate the balance of the energy generated with regard to the energy consumed in their manufacture and assembly (and even recycling). The EPBT is an indicator which units are years and indicate the time that passes until the energy generated by the modules is equal to the energy needed for his manufacture and assembly. The ERF is non-dimensional and it indicates the number of times that along the useful life overcomes the energy generated by the modules to the energy needed in his manufacture and assembly.

To study these values it is precise to know the Gross Energy Requirement (GER) in the modules of study, for which the following values, taken from the literature (Alsema 2006) (Raugei 2007), are used. They are showed in the following table:

Technology	Sc-Si	p-Si	CIS	CdTe	a-Si
GER (MJ/m ²)	5200	4000	4053	2281	2064

Other elements as structures, inverters, etc. know as Balance of System (BOS) must be included in the analysis of the gross energy of a PV system. In this paper, the GER for the structures has been estimated in 300 MJ/m²(Alsema 2000).

All together, in Zaragoza, the Final system yield is 1,258 kWh/kWp, and the energy requirements are, assuming a similar energy for the construction of the car:

- Electric car: 3,200kWh/year + 20,000kWh
- Conventional car: 3.75* 3200kWh/year + 20,000kWh

With the solar irradiation of Zaragoza, the actual PV technologies allow PV systems recover the energy needed in their manufacturing, transport and installation in less than 2 years.

In Zaragoza, the required annual energy required for powering the car can be supplied by a PV installation of some 2.5 kWp (i.e., 3200kWh/year / 1258 kWh/kW). The vehicle consumption would be offset by the installation of such PV power. With the 2.5kWp PV installation, the required energy in the construction of the car (20.000 kWh) is recovered (in Zaragoza) in 6.25 years.

The average life of the car, which is well below the panels (estimated in 25 or 30 years), should also be considered. Assuming the life time of the car as 15 years, it leads to:

15 years of yearly energy consumption + 6.25 years for obtaining the energy required for the production of the car + 3 years required for obtaining the energy required for the PV system (considering maintenance and inverter replacement) = 24 years

The resulting figure, 24 years, is below the PV systems life time expectancy. Therefore, with the 2.5 kWp PV system we would get electricity not only for that vehicle, but also for the energy consumed in the production of the car and the PV system and some extra electricity for other uses.

In economic terms, with the present prices of PV installation (3-3.5 €/kWp for fixed PV modules completely installed), an upfront investment of some 7,600-8,900 € would be required.

Assuming the life time of the modules 25 years (pessimistic estimation), it means a yearly cost of some 305-356 €/year, a much lower cost that the annual cost fuel needed with a conventional car (20,000 km, at 7 l/100 km, 1400 l/year, more than 1,600-2,100 €/year).

In an electric car, the average energy consumption is much lower, some 3,200 kWh/año; considering a price of electricity of 0.15 €/kWh, the economic cost of the yearly energy is 480 €/year. As we can see, the economic saving in fuel allows paying the PV installation (and recovery money) in the lifetime of the car. But we have some other important advantages: a much lower energy needed, obtained from a clean resource, without using any natural reserve, avoiding CO₂ emissions and other contaminants (cleaner vehicle) and fuel transport. As we said before, the energy cost of a conventional car fuelled by gasoline is 0.6 kWh/km, i.e., 3.75 times more. If this linking consumption to renewable generation is applied to a new conventional car, the capacity of PV needed reach 9.5 kWp. The upfront cost needed clearly disincentives these less efficient vehicles. With this mechanism, consumers will surely tend to use efficient technologies (electric car instead of conventional car) that allow their consumption and economy compatible with energy conservation.

Country	Location	Longitude	Latitude	Altitude	Y_f (kWh/kWp)
Spain	Cádiz	-6,24	36,53	0	1520
Germany	Berlin	13,4	52,50	44	882

Table. Coordinate and Y_f of the three selected locations

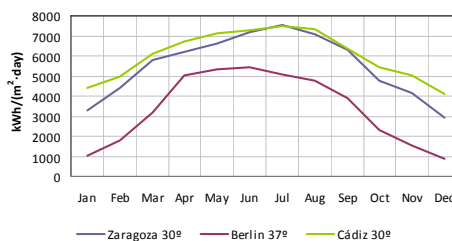


Figure. Radiation at optimal tilt in the three selected locations

The Spanish government is committed to have one million electric or hybrid cars on the Spanish roads by 2014. One measure to achieve this goal is to provide consumers who buy an electric car in Spain with a rebate of 15 % of the price of the vehicle. Instead of that a government policy could incentivise (or even create the obligation of) the installing the PV required according the mechanism above related. One Million of new electrical vehicles would mean an extra installation of 2.5GWp. A similar quantity of PV systems was installed in Spain in 2008 (just in one year!!!). This quantity is below the objective presented by the Spanish Photovoltaic Industry Association (ASIF) for that date. The plan of the Spanish government is to reach 13GW in 2020, while the initial estimation of ASIF was to reach 20GW by 2020. Linking this capacity to new electrical vehicles is totally possible.

Alternatively, different locations require different PV power for the same service. As a comparison, two additional locations have been analyzed. In the figure, the irradiation over optimum tilt in other two locations (apart from Zaragoza) is presented. One of the locations is Cadiz, in South Spain, with higher yearly irradiation than Zaragoza, and Berlin, in Germany, with much lower irradiation.

In Cadiz, with a Final system yield of 1,520 kWh/kW_p a PV system of 2.1kW_p is required, with an initial investment of 6,350 (considering a cost of 3.5 €/W_p) or 7,368 euro (considering 3 €/W_p) Assuming a lifetime of the PV system of only 25 years, the annual cost is 253-295 euro per year. Again, the required energy in the construction of the car (20.000 kWh) is recovered in Cadiz in 6.25 years (this time with 2.1kW_p). We have more radiation but we install less modules, so the recovery of the energy is obtained in the same number of years.

In Berlín, with a much lower Y_f, 892 kWh/kW_p, a PV installation of 3.6 kW_p is required (10,762-12,556 € of initial investment, 430-500 €/year).

Obviously, depending of the irradiation and climatic conditions of the site, the size of the installation that allow the generation of all the energy required for building a new car, powering it and recovery the energy of the PV system itself is different but with costs lower than the conventional case.

This is only an example of application of the CLR mechanism. Appliances as television sets, washing machines, etc could be linked with renewable energies in the same way.

5. CONCLUSIONS

The current rate of growing in energy demand is not sustainable. Efforts should be aimed to energy conservation and, where possible, to decrease the energy consumption. However, in a short time, there exists still the need of providing energy to those countries which are developing. An energy degrowth process can cannot be imposed to those developing countries or even presented has a necessary condition. Some alternatives must be provided. Although the first effort must be aimed to develop more and more efficient technologies, bearing in mind to avoid of the rebound effect, and to reduce the individual and collective demands, the opportunity given by the renewable energy sources has to be observed. A fast transition to renewable energies is needed. The Consumption-linked to-Renewable energies mechanism (CLR) has been presented in this work. With the CLR mechanism, every new unit of consumption must be associated to a new renewable generation. Within this proposed framework, consumers would invest in new renewable generation systems when buying any equipment. At the same time, they will surely tend to use efficient technologies that allow their consumption compatible with energy conservation.

The ideas presented in this paper try to contribute to the energy degrowth process, understanding it as a necessary defossilization process.

REFERENCES

- Abbott, D. (2009). "Keeping the energy debate clean: How do we supply the World's energy needs". *Proceedings of the IEEE*, Vol 98 (1): 42-66.
- Akella, A.K., Saini, R.P., Sharma, M.P. (2009). "Social, economical and environmental impacts of renewable energy systems". *Renewable Energy* 34: 390-396.
- Bayod-Rújula, A.A. (2009). "Future development of the electricity systems with Distributed Generation". *Energy* 34 (3): 377-383.
- Bayod-Rújula, A.A., Martínez-Gracia, A. (2008). "Dual use of solar power for electricity and water supply". In *Proceedings of the 6th Biennial International Workshop Advances in Energy Studies, Graz, Austria*.
- Edinger, R., Kaul, S. (2000). "Humankind's detour toward sustainability: past, present, and future of renewable energies and electric power generation", *Renewable and Sustainable Energy Reviews* 4: 295-313.
- EEA, 2008. *Energy related greenhouse gas emissions*. European Environment Agency. Available at: <http://www.eea.europa.eu>
- EEA, 2010. *Transport emissions of greenhouse gases (TERM 002)*. European Environment Agency. Available at: <http://www.eea.europa.eu>
- ESCWA 2001a. *Energy options for water desalination in selected ESCWA member countries*. Economic and Social Commission for Western Asia. United Nations
- ESCWA 2001b. *Water desalination technologies in the ESCWA Member Countries*. Economic and Social Commission of Western Asia. United Nations.
- Eurelectric (2004). *Eurelectric and UIE, electricity for more efficiency: Electric technologies and their energy saving potential*.
- Evans, A., Strezov, V., Evans, T.J. (2009). "Assessment of sustainability indicators for renewable energy technologies". *Renewable and Sustainable Energy Reviews* 13 (5): 1082-1088
- Fritzmann, C.; Lowenberg, J.; Wintgens, T. and Melin, T. 2007. "State of the art of reverse osmosis desalination". *Desalination*, 216 pp.1-76. Elsevier.
- Gabbrielli, E. 2008. "Nuevas fuente de agua: reutilización y desalación". *Water in the world. Semana Temática 10. Expo Zaragoza 2008*.
- Jefferson, M. (2008). "Accelerating the transition to sustainable energy systems". *Energy Policy* 36: 4116-4125.
- Nada Zamel, X. 2006. "Life cycle analysis of vehicles powered by a fuel cell and by internal combustion engine for Canada". *Journal of Power Sources*, Volume 155, Issue 2, 21 April 2006, Pages 297-310
- Rodrigue J.P., Comtois C. and Slack, B., 2009. *The geography of transport systems*. Routledge.
- Uche, J. et al. (2001), "Hybrid desalting systems for avoiding water shortage in Spain", *Desalination*, 138, 329-334.
- UN (2002) *World Population Ageing 1950-2050*. United Nations. Population Division, DESA.
- UN (2006) *Water, a shared responsibility*. United Nations. World Water Assessment Program. Unesco.
- Valero, A.; Uche, J. and Serra, L. (2001). *La desalación como alternativa al PHN*. Informe elaborado a petición del Gobierno de Aragón. Zaragoza.

HYDROELECTRICITY AS ALTERNATIVE IS A REAL CLEAN ENERGY? THE BELO MONTE CASE

*Antônio Libório Philomena**

Instituto Justiça Ambiental (IJA), Brazil

ABSTRACT

Brazil has 13% of the waters' Planet. The Amazon Region is covered by thousand of rivers and igarapés carrying different qualities of energy. The Amazon River flow is around 200,000 m each second. Today the Brazilian energy matrix is composed most by oil (35%), sugar cane (20%), hydroelectricity (14%), natural gas (10%), coal (6%), and other renew energies (4%).

With the country economic plans looking for 6% grow every year (although in the real life the mean Brazilian economic growth is around 3% at maximum), the use of rivers as a source of "clean energy" (compared with coal and oil) brings an urgent need of a new energy efficiency methodology.

When much important information are not in the hydroelectricity efficiency calculations, the term "clean energy" is just one more green washing. In this study we aggregated environmental and social variables to the hydroelectric energy project mixing the concepts of Emergy and Ecological Footprint to find new index of efficiency, investment ratios, CO₂ emissions and environmental loading. All the data come from the Belo Monte Hydroelectric Dam that the Brazilian Government plans to build in the Xingú River (State of Pará in the Amazonian Region). The dam will be the world's third largest with a potential installed output of 11,233 MW (and a modeled output of 4,462 MW that is less than 40% of the total installed) and a water body surface of 516 Km that will modify forests, igarapés, river flows, towns, and different cultures. Some places will be flooded while others will be drained. These modifications should be on the economic and electric chart calculations besides CO₂ emissions of all engineering components. The improvement proposed in the calculations brings old questions again: what is renewable energy? What it means "clean energy"?

Keywords: Hydroelectricity, clean energy, Brazil

* Presenting Author: Antônio Libório Philomena (alphilo@mikrus.com.br)

INTERNATIONAL COMPARISON OF THE EXOSOMATIC ENERGY METABOLIC PROFILE OF DEVELOPED ECONOMIES

*Arturo Andersen Chinbuah**

Department: Institut de Ciència i Tecnologia Ambientals (ICTA)

ABSTRACT

By applying the methodology of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM), this paper performs a comparison of the energy metabolic patterns of the USA, Canada and Australia that represent developed economies with low population density and a big surface with the energy metabolic patterns of the United Kingdom and Spain as developed countries with high population density and small size, for which there is published research.

Taking into account the relation between economic theory, complex system theory and thermodynamics this paper tries to link the evolution of the economic process to the use of energy, breaking down the economy from a whole, to the sum of its parts, making us able to see how each economic activity has a part and an effect on the whole.

In this particular case the existence of different patterns in energy consumption of the selected economies due to different size and population constraints is analyzed. In the cases of the selected countries a clear link between energy consumption and economic growth has been found, opening the search for finding attractor points on the evolution of their energy intensity over time.

Keywords: MuSIASEM, Energy intensity, economic labour productivity, exosomatic metabolic rate, total exosomatic throughput

JEL Codes: L60, L70, Q41, Q43, Q56, Q57

1. INTRODUCTION

Human societies have altered the environment in which they live from the early beginning of human time, to make the environment adapt to human needs, with labor and technology they tended to stabilize and improve their livelihood according to their aspirations as a society within the limits that the environment used to impose over them.

In biophysical terms, the process of self-organization of human societies is the ability to stabilize flows through the society, for their maintenance and reproduction, but after the discovery of fossil fuels and their exploitation, societies started to grow, to consume and to pollute beyond the environment's capability of absorption, not being sustainable and as said in '(Giampietro et al. 2001)': To be sustainable, the process has to be:

1. Compatible with the aspirations of the humans belonging to society;
2. Compatible with the stability of natural and human-managed ecosystems;
3. Technically feasible;
4. Economically viable;
5. Compatible with the mechanisms and institutions keeping coherence in society's interactions with its environment.

Energy intensity, defined as the relation between energy used per monetary unit obtained, is one of the topics, where many authors argue about its direction and the

* E-mail: arturouv@gmail.com; Telephone: +34963459187

causality between the two variables that conform it, GDP and Total Energy Throughput (TET), where throughput is the entropic physical flow of matter-energy from nature's sources through the human economy and back to nature's sinks. The economic process is a process of transformation of energy and matter for production and consumption of goods and services, also known as 'throughput', a term introduced by Herman Daly, cited in (Boulding 1993).

The intensity of use hypothesis put forward by (Malenbaum 1978), states that income is the main factor that explains consumption of materials, so in stages of economic growth countries will increase energy consumption at the same rate as growth of income until certain point was reached upon which there will be a de-linking and further increases of income will not increase energy use at the same rate. This hypothesis has later on been called the environmental Kuznets curve (EKC) (Chimeli and Braden 2005).

Many studies in favor of the Kuznets curve are based on the extrapolation of past historical cases into the future, not taking into account the Jevons' Paradox (Polimeni and Polimeni 2006)), overestimating the importance of efficiency for reducing the total energy use, they neglect the rebound effect.

2. METHODOLOGY

Multi Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) represents the performance of the systems in terms of a set of attributes by using parallel non-equivalent descriptive domains. As stated by (Giampietro et al. 2001): 'It builds on the energy analysis of human societies. Based on the fund-flow model of (Georgescu-Roegen 1975) made for studying the biophysical roots of economic processes, MuSIASEM allows tracking flows of matter and energy along with economic flows, and learn from the trajectory of development and to build robust scenarios. It has been developed for characterizing the viability and desirability of patterns of production and consumption of socio-economic systems.

2.1. How is MuSIASEM applied?

For applying MuSIASEM we first have to choose variables able to map the size of the system selecting funds and flows. Funds are able to transform input flows into output flows, they have a given identity at the beginning and retain the same identity at the end of the process and they perform certain functions for the system that need to be maintained. They entail a constraint on the rate at which flows enter and exit the system; examples of funds are hours of human activity, capital... Flows are consumed throughout the system to stabilize the activity of the funds (energy consumed, inputs) and are generated on the process (wastes, added value).

In order to describe the different economic systems we divide the systems in to three levels:

- Level N reflecting the whole economy:
- Level N-1 that divides the whole economy into two parts; the paid work sector, which generates added value that the household sector consumes it.
- Level N-2 the productive sector is divided into three subsectors: agriculture, productive sector (industry) and service and government sector.

After choosing those variables the nested hierarchical structure associated to the system has to be mapped, using ratios between funds and flows, resulting intensive variables that can reflect a biophysical accounting as well as an economic accounting (Table 2).

Indicators	Definition	Calculation	What does it measure?
EMR _s	Exosomatic metabolic rate, average of the society (MJ/h)	TEI/THA	Energy consumption per hour of human time available to the society
EMR _i	Exosomatic metabolic rate sector i (MJ/h)	ET _i /HA _i	Energy consumption per working hour in sector i
EI	Energy Intensity (MJ/\$) for the whole economy	TEI/GDP	Energy consumption per unit of added value in the economy
EI _i	Energy Intensity (MJ/\$) for sector i	ET _i /AV _i	Energy consumption per unit of added value in sector i
ELPi	Economic labour productivity (\$/h) sector i	AV _i /HA _i	Added value per hour of working time in sector i
ELPi/EMR _i	Energy efficiency of production (\$/MJ) for an economic sector	AV _i /ET _i	Added value generated per unit of energy consumption in sector i

Table 1. Variables used in MuSIASEM

Where i represent the sectors of paid work and household and the subsectors of agriculture, production and service and government

Variables	Definition	Description	Calculation
THA	Total human activity	Total available human time a society has to perform different activities, measured in hours (h)	Population times 8760h
TET	Total energy throughput	Total primary energy used in an economy in one year, measured in Joules, (J)	Statistical sources
GDP	Gross domestic product	Added value generated by an economy in one year, measured in constant U.S. 1990 \$	Statistical sources
AV _i	Added value in sector i	Added value generated in sector i, measured in constant U.S. 1990 \$	Statistical sources
HA _i	Human time in sector i	Human time allocated to sector i per year measured in hours	Population in sector i times annual worked weeks per year times average working hours per week in sector i
ET _i	Energy throughput in sector i	Primary energy used in sector i in one year measured in Joules	Statistical sources

Table 2. Indicators used in MuSIASEM

Metabolic systems are open dissipative systems (Nicolis. and Prigogine. 1977) that operate in multiple scales, they have two parts that maintain an equilibrium: one generating an hypercycle (Ulanowicz 1986), that provides energy for the functioning of the system (the energy sector in our case) and a dissipative part that uses the surplus of energy production and uses it for the maintenance and growth of the system(self reproduction).

As specified on (Giampietro et al. 2001) the skeleton of MuSIASEM is based on: The socioeconomic system (country, economic sectors, economic subsectors, individual economic activities and households); the allocation of human activity; mapping of the systems biophysical and economic variables.

3. RESULTS

3.1. Australia

Level N

The energy intensity in Australia has decreased, as [figure 1](#) shows, in a moderate way. As the Australian GDP grew faster than the TET, due to the fact that the economy is moderately switching to less energy intensive activities, moving to a service economy.

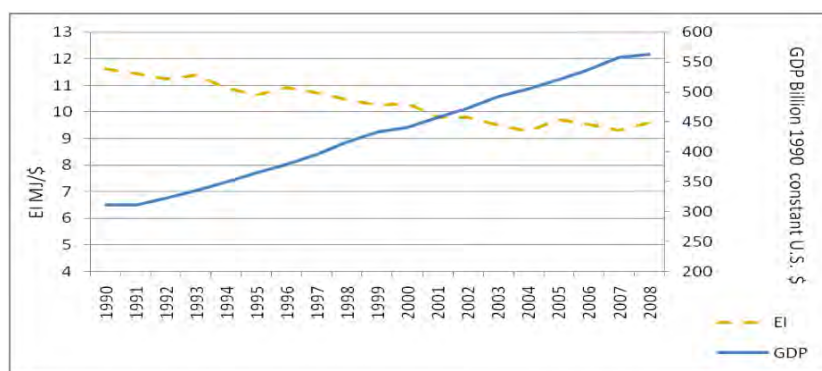


Figure 1. Australia's Energy intensity and GDP

TET and GDP have similar tendencies during the period studied, until the year 2000 where TET grows less, due to slowdown on Australia's productivity, related to unusual developments in the mining industry, the effects of droughts and the overstatement of productivity, for more information refer to (Dolman (2009)).

As expected on this kind of economy, EI decreases while the GDP increases, so a part of the explanation on the increase of the TET is due to an increase on GDP that has grown faster than the population, translating on an increase on the energy consumption per capita, being this the reason why TET rises when EI is decreasing.

In an overall look at the consumption of individuals in Australia, taking a look at the megajoules per capita consumed it is the only country of the three studied that grows their energetic consumption without having reached a peak, that may be near the values reached by the other two countries.

Level N-1

In this case, EMR_{PW} and ELP_{PW} show similar tendencies, which shows that there is not yet a decoupling of both, probably the importance of mining in this country explains why ELP_{PW} follows the path of EMR_{PW} in the whole context, where the growth of EMR_{PW} is mostly explained by the growth of EMR_{PS} and EMR_{SG} . The growth of ELP_{PW} shows that added value is growing in time, probably because of the rise in the added value of the industrial sector and especially because of the rise in added value in the service sector

that has also have the biggest increase in hours allocated for their providence. This result makes us hypothesize that economies with lower level of capitalization may have a clearer relation between EMR_{PW} and ELP_{PW} , such as in the case of Spain in (Ramos-Martin 2001), Ecuador in (Falconi-Benitez 2001) and the cases of post war Germany, France, Japan and the U.K. in (Kaufmann 1992), the Spanish case will be discussed further on the discussion section.

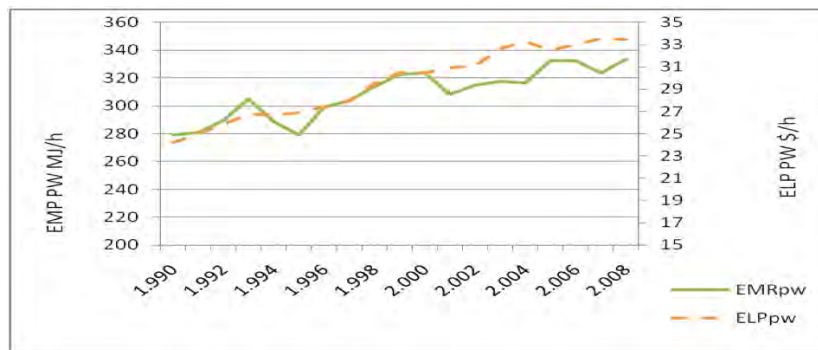


Figure 2. EMRpw and ELPpw of Australia

At the household level the EMR_{HH} has been growing slowly and steadily and on a higher rate than EMR_{PW} , showing that households have been capitalizing because they were on a lower standard than the other two countries, still remaining less capitalized though.

Level N-2

There is no significant change on the metabolic rates, the agricultural sector maintains its EMR more or less constant during the period of study, while the industry sector shows an increase on its EMR that peaks and slowly declines, this increase is due to a higher increase on ET_{PS} than on HA_{PS} , meaning that there is still a capitalization process that is partly explained by the importance of minning in this country that during the period tripled its energy requirements.

The service and government sector just has a slight increase on its EMR, this is explained by the fact that the increase of energy use in this sector is produced by the increase on hours allocated to its production. The decrease on the energy intensity at level N is explained by the service and the industry sectors. The economy has undergone a process of structural change resulting in an increase of the share of GDP coming from services.

ELP from the subsectors grew moderately, as it will be expected on an industrialized economy, ELP_{SG} is lower than ELP_{PS} due to the importance of mining in the country.

3.2. Canada

Level N

Canada also has also effectively decreased its energy intensity as can be seen on the figure below having a constant growing GDP, matching the expectations of a developed economy.

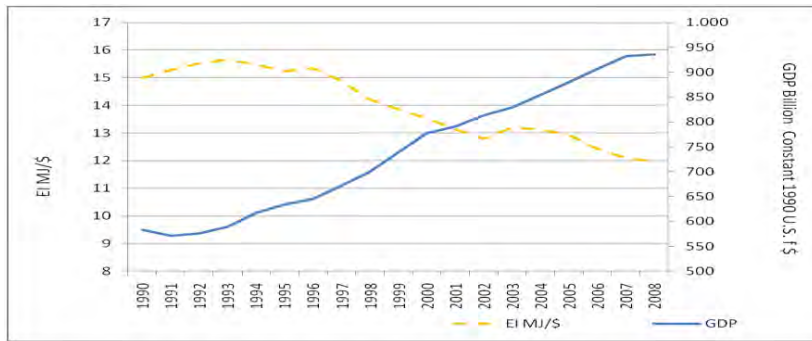


Figure 3. Energy intensity and GDP of Canada.

Canadian GDP had a similar increase as the energy throughput, but GDP grows in a faster way until they more or less show a tendency to become stagnant, what can be seen maybe as an dematerialization, energetically speaking, were GDP continues to grow without an increase in the energy use, probably arising from the increase on the value on extracted ores from the country.

In the case of Canada, energy consumption per capita reaches a peak in 2005 and declines the following years.

Level N-1

In this economy the ELP_{PW} and EMR_{PW} still have a related evolution due to the importance of mining in this country, but after 1996, as it can be seen on [figure 4](#) that the movement of both intensive variables starts to taking different directions.

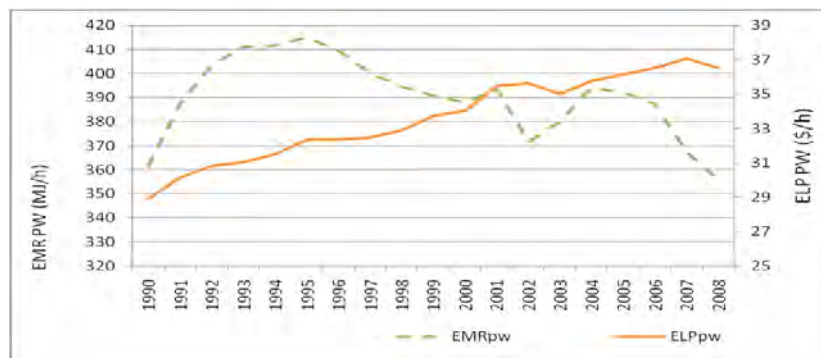


Figure 4. Evolution of EMR_{pw} and ELP_{pw} in Canada.

EMR_{HH} has remained quite constant showing that the material way of life in Canada has become stagnant, while EMR_{PW} seems to have reached a peak in the middle nineties, explained by the increase on working time that overweighs the increase of the total energy use, meaning that the system is becoming more energy efficient.

Level N-2

As stated before Canada's EMR_{PW} reached a peak in the middle 90's, when EMR 's from the industrial and the service and government sectors also reached a peak and then start declining, agriculture is the exception, with growth in energy spent per hour, explained by the need to feed a growing population in a country with hard climatic conditions and the shift of workers from agriculture to other sectors. The decrease on EMR_{PS} goes against the high increase on the EMR of the mining industry that more than doubles during 20 years from an EMR of 596MJ/h to 1262MJ/h, mining represents more than a 10% of the total energy consumption of the sector, so the other industrial activities

are getting more efficient as the increase on the total ET_{PS} is not as significant as on the mining industry.

The increase of the system's energy consumption is due in a great measure to the service and government sector, and partially to the household sector, been both cases derivable from an increase on the population.

Even though Canada also has effectively decreased its energy intensity, the greatest importance of this decrease comes from the industrial sector, because there are hardly any changes in the other two. This is explained by the increase on the added value in the industrial sector, derivable from an increase on the price of the ores exported by the country.

The increase of the total energy throughput is mainly occasioned by the increase on the energy throughput of the service sector that grows over a 35% on the studied period, so the decreased of the energetic intensity of the economy is outweighed again by the increase on the size of the system.

3.3. The USA

Level N

As can be seen in [figure 5](#), the energy intensity of the U.S. also decreases, proportionally more than in the other two cases.

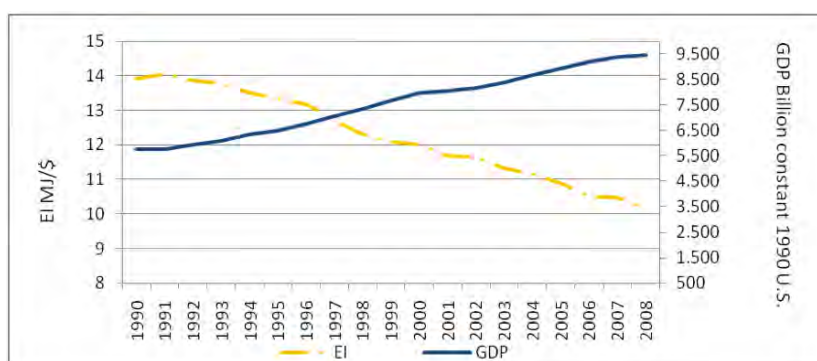


Figure 5. Energy intensity and GDP Evolution on the U.S.

As it can be seen on the figure above United States EI has been decreasing from 14MJ/\$ until nearly 10MJ/\$ with a much more steady path than in the case of the other two countries, mostly explained by their productive sector and their services, which have experienced a much higher growth on added value than on their energy requirements. The U.S. has become more efficient creating added value per joule used in the system, that has kept increasing its ability to transform more energy, mostly due to the increase on the energy throughput of the service sector that has grown in size.

The overall tendency of the economy looks positive as GDP and TET could decouple on the future where the increase of GDP could not need and increase on energy use, showing a clearer sign of dematerialization than the other two countries.

Adding to the dematerialization hypothesis on energetic terms for the U.S, the consumption of energy per capita decreases from the year 2000, reaching lower levels than those at the beginning of the period of study.

Level N-1

Concerning the evolution of ELP_{PW} and EMR_{PW} [figure 6](#) shows how the United States has been successful on generating added value without an equivalent increase of energy consumption, the productive sector is the sector that mostly contributes to the

growth of EMR_{PW} due to a capitalization process, but the overall divergence of both variables can be explained thanks to the decrease of the importance of the agricultural sector.

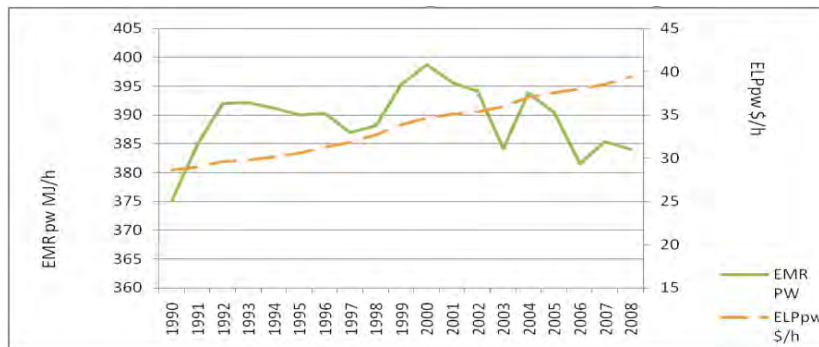


Figure 6. EMRpw and ELPpw of USA.

At the household level there has not been much of a change, just a moderate increase, confirming the stagnation of material life.

Level N-2

EI on the U.S. has declined mostly because of the industrial and service sector, which has experienced a much higher growth on added value than on their energy requirements. In the first case, there has been an increased on added vale and a decrease on population working in that sector, thus increasing the energy requirements, but there has been a major shift of population from the industrial sector and the agricultural sector to the service sector, hence making the economy move to a service economy, with a greater added value and with a growing sector that consumes less energy.

The increase on ET_{SG} is due to a bigger part of the population working in that sector. In the case of the industrial sector the increase of its energy use is caused by the need of an increase in production for a bigger society with less people working on production.

The ELP of the U.S. has grown thanks to increases in the ELP_{PS} and ELP_{SG} , where both sectors have grown on their ability to create added value while the agricultural sector has remain quite steady, even with the subsidies it receives.

4. DISCUSION

The overall tendency of this economies is to reduce their EMR_{PW} until a stabilization point that could be near 350MJ/h. Australia as its EMR_{PW} is lower it is still growing, showing this that the U.S and Canada are more capitalized than Australia, even if the changes in EMR_{PW} of the three countries is occasioned by the structural change from PS to SG.

Changes in EMR_{PW} in Canada and the U.S. show the same type of movements, EMR_{AG} grows in both countries. On the industrial sector both countries have reached, a ceiling Canada in 1993 and the U.S. 2004, meaning that in the U.S. as population grew and human time allocation moved towards the service sector the industrial sector needed to capitalize to substitute human labor, whereas in Canada EMR_{PS} the increase on energy consumption was compensated by the increase in HA.

Concerning to EMR_{SG} Canada has a quite stable consumption per hour reaching a maximum consumption per hour in 1995 that then declines showing that the increase in ET_{SG} is due to the increase on the population working in that sector. The same happens to the U.S. where EMR_{SG} is also quite stable reaching its maximum value in 1996 and then

stabilizes, making the last statement from Canada also true for the U.S. In contrast Australia has not reached a peak on EMR_{PS} meaning that the increase in labor of the sector is not as high as the increase on the energy consumption, so the sector is still capitalizing, and its service sector has not reached a peak.

All this shows that these economies show similar characteristics, but Australia is still growing because it is behind the other two.

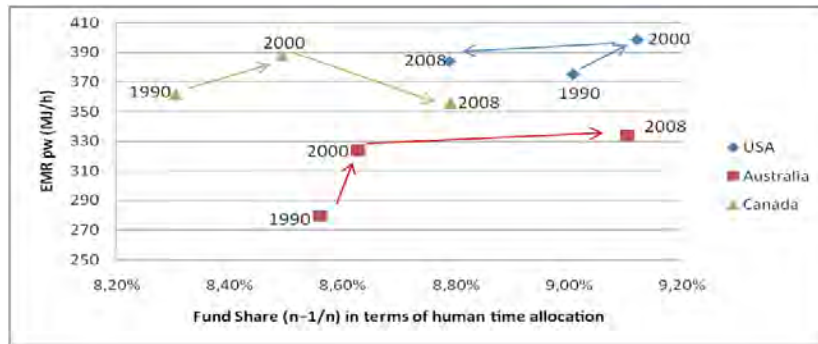


Figure 7. Fund Share ($n-1/n$) in terms of human time allocation.

Looking at their ELP, they have the same kind of patterns and they are more or less situated at the same level, being a value from 33.5U.S.\$/h the value of ELP in 2008 for Australia 36.5U.S.\$/h in Canada and 39.4U.S.\$/h in the U.S.

Starting with agriculture Australia shows the biggest increase, from 13.1U.S.\$/h in 1990 to 23U.S.\$/h in 2008, in Canada ELP_{AG} ends at 22.48U.S.\$/h in 2008 with an increase of 5\$ hour since 1990 while in the U.S. the increase is just of 4\$ with a final value of 20.9U.S.\$/h, all this increases are produced thanks to subsidies to the agricultural sector. The industrial sector performs better: Australia passes from 24.3U.S.\$/h to 34.7U.S.\$/h, the same happens in the USA where ELP_{PS} grows from 29.2U.S.\$/h in 1990 to 43.5U.S.\$/h in 2008. In the case of Canada ELP_{PS} has an increase from 28.1U.S.\$/h to 37.29U.S.\$/h, this increase is explained by the increase in value of their mining exports. ELP_{SG} shows the same movement in the three countries, increasing in all of them, this is easily explained by an increase on the quality and type of services offered.

Exploring the relation between these two variables; in the case of the U.S., these two variables evolve differently having ELP_{PW} a higher increase than EMR_{PW} , being this what makes the U.S. a reference on economic growth without a big increase on ET. Canada is also following the same patterns also accomplishing the goal of separating economic growth and energy consumption. This could take us to think that decoupling of both variables might come after high consumption rates are reached.

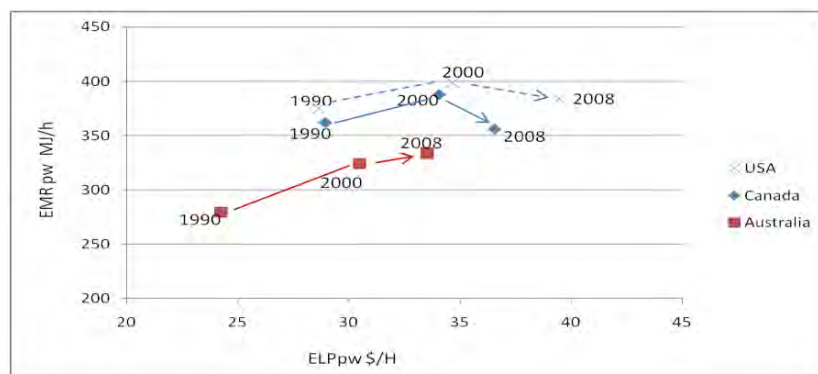


Figure 8. Comparison of EMR_{pw} and ELP_{pw}

On this discussion I will compare results found on this study with results found by (Ramos-Martin 2001) that studies energy intensity in Spain and with results from in (Gasparatos et al. 2009) for the U.K. comparing developed economies with different level of industrialization, and population to land ratio.

	SPAIN	UK
EMR_{HH}	1.67 MJ/H in 1976 to 3.27 MJ/H in 1996	5.7 MJ/h in 1981 to 7.5 MJ/h in 2004
EMR_{PW}	92.92 MJ/h in 1976 to 138.13 MJ/h in 1996	134.2 MJ/h in 1981 to 130.6MJ/h 2004
EMR_{AG}	18 Mj/h in 1976 to 43Mj/h in 1996	66.4 MJ/h in 1981 to 49.9 MJ/h in 2004
EMR_{PS}	220 MJ/h in 1976 to 338MJ/h 1996	291.5 MJ/h in 1981 to 476.7 MJ/h in 2004
EMR_{SG}	40 MJ/h in 1976 to around 59 MJ/h in 1996	37.5 MJ/h in 1981 to 29.9 MJ/h in 2004

Table 3. Main finding in the U.K in (Gasparatos et al. 2009) and Spain in (Ramos-Martin 2001)

A difference between Spain and the UK with the other 3 countries, is that at the household level this two last countries have not gotten, in the period of their relative studies, to a stagnant material way of life.

Taking a look at EMR_{PW} , the U.K. shows a behavior similar to the analyzed countries with an EMR_{PW} that is stagnant, while in Spain it grows, due to the fact that Spain was parting from lower levels of consumption.

This two countries show much lower EMR_{AG} than in the U.S., Canada and Australia, this difference is based on their size. EMR_{PS} is also much higher on the three big countries than in Spain and U.K.; The cases of Canada and Australia are explained by the importance of their mining and quarrying that are energy intensive, while in the U.S. this big difference can be explained by the importance of their whole industry, that exports to all over the world, adding to that the fact that the percentage of human time allocated to the productive sector in the U.S. (20%) is much lower than in Spain (30%) or in the U.K. (82%).

The issue of space also explains a big difference between these countries, Spain and the U.K. have very small EMR_{SG} compared to the other three countries, transport sector accounts for a big part of the energy per hour consumed in this sector, and due to the size of this three systems transport is much bigger.

5. CONCLUSIONS

The MuSIASEM analysis made in this paper has shown how the economic system energy consumption and time use have evolved in different countries through time, enabling us to compare Australia, Canada and the U.S. as big and extensive economies among themselves and between smaller countries in size. This whole analysis shows that the inverted 'U' curve applies for this three countries to a more or less extent being the U.S. the most clear example and Australia the lesser, compared to the case of Spain that does not follow this hypothesis, meaning that different countries may have different thresholds in order to start dematerializing or just that this hypothesis cannot be applied to all the economies.

This approach has aired that these developed economies are all shifting their economic activity from agriculture and industries to the service sector.

Another interesting point that this study shows is that economies might grow on their total exosomatic throughput, exosomatic metabolic rate on the paid work sector, megajoule consumption per capita, but at a certain point will stabilize their total energy

consumption, their energy consumption per hour, probably happening when the economy stabilizes and the growth of the system stops outweighing the efficiency gains.

But what it is shown is that the extension of a country plays an important role, whereas small heavily populated countries might try to be more efficient due to restrictions of space for waste sinks, (as said in (Ramos Martin J. 2005): 'A crucial problem may not be input scarcity but sink scarcity'), building, inland traveling and all kind of restrictions that space might cause, while large countries would not take into account this kind of restrictions. Thus using complex system theory it might be stated that the hypercycle maintaining the whole system does depend on the size of the system, and the autocatalytic loop, that is growth enhancing, is higher in large scale economies and the dissipative function of the system also is dependent on its size.

What looks as a positive sign towards dematerialization on energy terms, but if all the economies show the same patterns as the ones analyzed on this paper the total amount of energy to be delivered to human use might be too high to be sustained.

Data used in the analysis:

The disaggregation by sectors for the 3 economies: Energy Balances of OECD Countries - Economic Indicators Vol 2010 release 01

GDP, added value and population data obtained from: U.N. National accounts main aggregates database.

Data on employment gathered and working hours per economic sector from: Laborsa main statistics 2010.

REFERENCES

- Boulding K.E., 1993. *Steady-state economics: Second edition with new essays : Herman E. Daly*. Island Press, Washington, DC, 1991, 302 pp., ISBN 1 55963 072 8. *Ecological Economics*, 7:179-180.
- Chimeli A.B. and Braden J.B., 2005. "Total factor productivity and the environmental Kuznets curve." *Journal of Environmental Economics and Management*, 49:366-380.
- Dolman B., (2009). "What Happened to Australia's Productivity Surge?" , 42 , Issue 3, pp 243-263.
- Falconi-Benitez F., 2001. "Integrated assessment of the recent economic history of Ecuador". *Population and Environment*, 22:257-280.
- Gasparatos A., El-Haram M. and Horner M., 2009. *Assessing the sustainability of the UK society using thermodynamic concepts: Part 1. "Renewable and Sustainable Energy Reviews"*, 13:1074-1081.
- Georgescu-Roegen N., 1975. *Energy and Economic Myths*. "Southern Economic Journal", 41:347-381.
- Giampietro, Mayumi K and G.F. Bukkens S, 2001. *Multiple-Scale Integrated Assessment of Societal Metabolism: An analytical tool to study development and sustainability*.
- Giampietro M., Sorman Hadiye., 2010. *Assessing the quality of alternative energy sources: Energy Return On the Investment (EROI), the metabolic pattern of societies and energy statistics*.
- Kaufmann R.K., 1992. "A biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change". *Ecological Economics*, 6:35-56.
- Malenbaum W., 1978. *World demand for raw materials in 1985 and 2000*.
- Nicolis. and Prigogine., 1977. *Self-Organization in Nonequilibrium Systems*.
- Polimeni J.M. and Polimeni R.I., 2006. "Jevons' Paradox and the myth of technological liberation". *Ecological Complexity*, 3:344-353.
- Ramos Martin J., 2005. "Complex systems and exosomatic energy metabolism of human societies". :34 - 42.
- Ramos-Martin J., 2001. "Historical analysis of energy intensity of Spain: From a "conventional view" to an "integrated assessment"". *Population and Environment*, 22:281-313.
- Ulanowicz, 1986. *Growth and development: ecosystem phenomenology*.

THE CIRCULAR FLOW OF CO₂ EMISSIONS EMBODIED IN INTERNATIONAL TRADE

Alexandra Marques , João Rodrigues and Tiago Domingos*

Instituto Superior Técnico, Portugal

ABSTRACT

In the circular flow of economies, goods and services flow in one direction and associated payments flow in the opposite direction. Consumers (buyers) and producers (sellers) embark on voluntary exchanges making them better off.

Consumption-based inventories measure upstream CO₂ embodied emissions in a country's final demand, considering that consumers benefit from the CO₂ emissions generated. An obvious symmetrical view of the emissions embodied in final demand is the emissions embodied in the payments made for primary inputs, being the producer the one benefiting from it. These are the downstream embodied emissions.

Nowadays, international trade enables the geographical separation between consumption and production processes allowing for countries to benefit from emissions occurred elsewhere. Several studies have been made to understand how upstream embodied emissions flow between world regions. However, none have been made regarding downstream embodied emissions.

In this paper we compute both upstream and downstream emissions embodied in international trade between six world regions. For that we built a multi-regional input- output (MRIO) model using the GTAP 6 database. Quantification of these emissions, for the year 2001, reveals that a large proportion of CO₂ (~20% of the world total) is traded internationally. Three world regions concentrate 80% of the emissions: Developed Economies, Asia and Fossil Fuel Exporters. Developed economies import ~54% of world's total upstream embodied emissions in international trade. At the downstream level Developed economies import ~42% of world's total downstream emissions embodied in international trade, mainly from Fossil Fuel exporters and Asia. Machinery and equipment and fossil fuels are the sectors with more contribution to this phenomenon.

This shows that Developed economies are highly dependent on emissions occurring in Asia and Fossil Fuel exporters, not only to fulfill their consumption patterns but also to allow payments to their primary factors of production. At the downstream level, the flow of emissions from Developed economies to Fossil Fuel exporters is also relevant (~32% of the world's total downstream emissions embodied in international trade). The most important sector contributing to this import of emissions is the fossil fuels sector.

These results show that Fossil Fuel exporters, in order to receive payments for fossil fuels, greatly benefit from emissions occurring in Developed economies.

In the context of global climate policy, if both upstream and downstream emissions are considered, policy design can become more effective and equitable, and thus perceived as fairer, since every economic transaction is beneficial for both producers and consumers. This will stimulate the worldwide acceptance of and compliance with climate policies.

Keywords: international trade, upstream embodied CO₂ emissions, downstream embodied CO₂ emissions, circular flow, multi-regional input-output model (MRIO)

* Presenting author: Alexandra Marques (alexandra.marques@ist.utl.pt)

SOCIETY PERCEPTION OF ENVIRONMENTAL RISKS

Alberto Pasquini , Alessandra Tedeschi*

Deep Blue, Rome, Italy

ABSTRACT

Society seems to have a limited perception of the impact the current pattern of energy consumption could have in the future, and the social and economical dramatic changes implied in a "non planned" decline of the traditional energy sources. This happens in spite of the presence of some early signs of the risks involved, such as the scientific evidence of the human involvement in the global warming and studies showing the problems originated by uncontrolled use of non renewable resources. The reason of this limited sensitivity to the lessons and feedback that should come from our past behaviour has several and complex causes. This paper will focus on the factors influencing risk perception and especially on the ability to learn from past experience, moving from domains such as aviation and healthcare. In these domains monitoring and managing risk perception and learning from past experience are important objectives, that are pursued with systems designed for the purpose with different degrees of success.

Keywords: Communication, Incident Reporting, Learning from Experience, Risk Perception, Scientific Dissemination

1. INTRODUCTION

To modify the current pattern of energy consumption will require important social and behavioural change, that will not be possible without the commitment and active participation of our society. These commitment and active participation will be mobilised only if there is a correct understanding of the importance of the issues involved, that is, the impact the current pattern of energy consumption could have in the future, and the social and economical dramatic changes implied in a "non planned" decline of the traditional energy sources. But, nowadays the society seems to have a limited perception of these issues.

This is happening in spite of the presence of some early signs of the risks implicit in the current development model, and of the consequences implied in the use of fossil energy. For example, the idea that the temperature is rising because of the green house effect has now substantial scientific evidence and the glacier retirement and snow fall reduction are direct real life experience of any mature adult. There are accurate and consolidated studies showing the problem of past societies with the abuse of environmental resources, including non sustainable levels of energy consumption [Flenley et al., 2003], and some of these studies should be well known because of their considerable editorial success [Diamond, 2005]. This evidence should be clear and strong enough, but the human society seems not so worried by these early signs and unable to learn from past mistakes.

There are areas where the process of monitoring and managing risk perception and learning from past mistakes are very important objectives, especially for those organisations that are safety critical, that is, where errors and malfunctions could lead to severe incidents and accidents with losses in terms of human life. In particular, aviation is a domain where organisations were very successful in using knowledge from past events

* Corresponding author; E-mail: alberto.pasquini@dblue.it; Tel. + 39 06 8555208

and incident to improve the safety and efficiency of their services and products [Farrow et al., 2002]. The most prominent experience in incident reporting is the Aviation Safety Reporting System (ASRS), established in 1975 by the Federal Aviation Administration and the National Aeronautics and Space Administration. This is often mentioned as the best practice in incident reporting, due to its long-standing duration and due to the fact that it is almost unanimously regarded as a useful system. Unfortunately, even though many other attempts have been made in other various domains to establish similar systems to learn from past mistakes, very few can claim similar results [Department of Health, 2000]. Different success and failure factors have been discussed in the literature, spanning all levels of analysis and explanation [Johnson, 2002]. It appears that the ability to perceive risks and to learn from past experience and mistakes in complex organisations is influenced by several factors, some of which are intrinsic in the process of learning from experience, while others are characteristic of the domain and of the ultimate goal of the learning process [Pasquini et al., 2010].

Section II of this paper will analyse some of the formal and informal processes that our society and public and private organisations are using to learn from past experience and mistakes. Section III will present some instructive and representative examples of failures in these processes. Section IV will analyse the most important factors that influence the ability of the human society to perceive risks and to learn from past experience and mistakes.

2. EXAMPLES OF LEARNING PROCESSES

Learning and adjusting the behaviour on the basis of past experience and mistakes is a common process for humans and is essential for improving human knowledge. This process can take a variety of forms and applications, be done at the individual, organisational or social level, be implicit or explicit and with different levels of formality. This Section will illustrate this variety of forms through a few examples of different learning processes.

In Section 1 we introduced the ASRS of the Federal Aviation Administration. This is a well structured system built just for the purpose of learning from the feedback and problems of the past, and to support policy making in aviation safety with empirical data from the operational field [Billings, 1998].

Pilots, air traffic controllers, flight attendants, mechanics, ground personnel, and others involved in aviation operations submit reports to the ASRS when they are involved in, or observe, an incident or situation in which aviation safety was compromised. All submissions are voluntary. Reports sent to the ASRS are strictly confidential.

The core part of an ASRS report is a narrative of the event. This is provided in a free text format. Each report received by ASRS is screened against established criteria to determine if it warrants full analysis and if it should be entered into the database. Reports that undergo full processing fall into four categories: (i) aviation hazards that require immediate alert messaging, (ii) priority safety concerns that have been targeted for data collection, (iii) random sample to ensure database representativeness, (iv) reports that, based on the discretion of the expert analyst, represent a new or unique learning opportunity. After the initial screening, the report is further analysed. The first aim of the analysis is to identify any aviation hazards and flag that information for immediate action. When such hazards are identified, an alerting message is issued to the appropriate Federal Aviation Administration office or aviation authority.

The ASRS has been extremely successful and contributed significantly to increase the flight safety in developed countries. However, the application of similar system to different domains (e.g. railways, healthcare) did not produce similar positive results. The UK National Reporting and Learning System (NRLS) was set up by the National Patient Safety Agency to collect information about patient safety issues and to produce wider dissemination of lessons from serious incidents [Carruthers et al., 2006]. The primary aim

of the system is to provide an overview of the extent and the nature of harm within the National Health Service (NHS) and to develop solutions on a national scale.

As opposed to ASRS (confidential system), NRLS had been set up as an anonymous system to encourage reporting and to provide a more representative picture of the extent of harm across the NHS. In order to assess the nature of harm NRLS requires information about the factors contributing to incidents. The reporting process may include up to 6 different steps and some of the details which the reporter should fill in are related to the where, the what and the how, with a level of complexity that well reflects the healthcare domain (departments and specialities, phase of care, roles involved, etc.).

However, in spite of an admirable approach that expanded on the ASRS's experience to include state-of-the-art theories of organisational safety, the NRLS experience cannot be considered a success story. In 2006 the Department of Health issued a report called "Safety First" to reflect on the past experiences [Carruthers et al., 2006]. According to this report, the NRLS has not been very effective till now: "Despite the high volume of incident reports collected there is little evidence that these have resulted in actionable learning for local NHS organisations. The NRLS is not yet delivering high-quality, routinely available information on patterns, trends and underlying causes of harm to patients"

The two examples presented till now are cases of systems built specifically for the purpose of learning from the experience, from feedback and from early signs of effect of human actions. However, this learning process is inherent in the human communities and in most of the cases it is informal and not organised. It represents a key element for the scientific and technological progress. For example, the history of bridge design shows how progresses are clearly based upon experience [Tyrrell, 1911], and the past history of bridge failures is of special concern for structural engineers in trying to learn lessons vital to bridge design, construction and maintenance [Biezma et al., 2007].

This learning process represents also a key element for larger and less uniform human communities, and may influence social relations, policies, and interactions among peoples. For example, the planning of land use shows the importance of considering the influence of past decisions on geology, environment, transportation, citizen distribution etc. For all these elements experiences and feedback from the past are extremely important and play a key role in decision making, even if this is role is mediated and sometime overcome by political, social and economical considerations.

3. FAILURES IN LEARNING FROM MISTAKES

The process to learn from past experiences and errors can have a variety of forms and be based on well organised and planned systems built for the purpose or on informal and unplanned initiatives. It is a complex process that can take a variety of different forms and be influenced by several different factors. These factors can play a key role in hampering the learning process bringing to unexpected repetitions of past failures and mistakes, as we will see from the examples described in this Section.

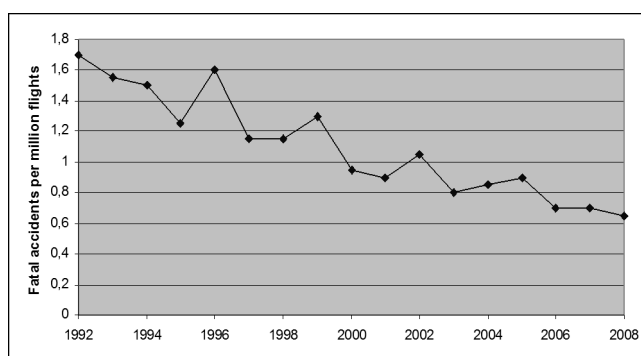


Fig. 1. Number of fatal aviation accidents per million flight

We discussed the successes of the safety reporting systems used in aviation and in air traffic control. In combination with other safety initiatives, these reporting systems contributed to increase flight safety, reducing significantly the number of fatal accidents per flight as shown in fig. 1. However, there were cases in which dramatic accidents resulted as a consequence of a combination of negative events that showed up several times in the past and for which no corrective action was taken.

The 2nd of July 2002 a flight of Bashkirian Airlines collided with a cargo flight of DHL in the airspace above Uberlingen close to the Costanza lake. All passengers and crew members of the two flights died in the accident. The investigation has shown that the accident was due to several reasons including the different operational procedures used by pilots in Russia and in the Western Countries in case of emergency, and the late and wrong instructions given by the air traffic controller of the control centre of Zurich, who was controlling the airspace where the aircraft were flying [Johnson, 2004]. This controller was alone and working on two different control work positions at the same time, because the other controller on duty was resting in another room for the night. This was against the regulations, but had been a common practice for years and was known and tolerated by management. When the controller realised that the situation had subtly increased beyond his span of control, it was too late to call for assistance. The same air traffic control centre had experienced two airprox incidents (two aircraft going dangerously close to each other) during single man operating procedures. Concerns had been raised by the Swiss Federal Office of Civil Aviation, but the control centre of Zurich argued that these practices were common in other European states and internationally. These airprox incidents represented valuable learning opportunities that were missed before the Uberlingen accident. This was due to several causes including: the cost of addressing the issue; lack of communication between the different stakeholders of the learning process; the wrong evaluation of the risk.

We have spoken of the progresses in bridge engineering and of the contribution given to this by the learning process. The resonant vibrations should be one of the most well understood and anticipated phenomenon in bridge design. However, the London Millennium Footbridge was closed only two day after its official opening because of unexpected lateral vibration due to resonance caused by people walking along the bridge. The bridge is a steel suspension bridge for pedestrians crossing the River Thames in London. Built between 1998 and 2000 it was closed for almost two years to eliminate the wobble entirely and reopened in 2002. The design error and the inability to use past experience on the same subject was due to several causes including: the complexity of the resonance problems that can show up in unexpected forms; the wrong evaluation of the real operational conditions of the bridge; the aesthetical needs that forced the adoption of some unconventional engineering solutions [Dallard et al., 2001].

Failures are even more frequent when the process of learning from the experience is a spontaneous, informal and not organised process, and when it is affected by political, social and economical considerations. Sicily is well known as an Italian region with high hydrogeological risk and its recent history is disseminated by landslides having disastrous impact on towns and their inhabitants. Figure 2 shows the risk maps resulting from two different public studies conducted between 2004 and 2008. Both evidence the area in the circle as one of the more risky because of the specific hydrogeological conditions. A landslide occurred in October 2009 in Giampileri (located just in the middle of the circle) with 18 fatalities and extensive destructions of the town. No actions had been taken after the studies to prevent the event. On the contrary new houses were built in what was (after the event) considered as the equivalent of a riverbed. Once again there were several causes for the apparently illogic behaviour of the Giampileri's citizens and politicians. These included: lack of communication and lack of perception of the risk; high economical revenues from the investment in new houses; tendency to release new construction permits to obtain short term political advantages.



Fig. 2. Risk maps resulting from different hydrogeological studies.

A second example of the same type comes from the former Soviet Union. Starting from the early fifties there were several significant, centrally planned, intervention to increase agricultural production with artificial irrigation of large portions of land. In most of the cases the uncontrolled drainage of water and the diversion of rivers ended up with severe damages to the environment. Possible examples are the Virgin Lands Campaign launched in 1954 by Nikita Khrushchev to open up vast tracts of virgin territories of the northern Kazach and Altay regions, and the colonization of the Kalmykia lands in 1958 where bad planning of agricultural and irrigation projects resulted in widespread desertification. In spite of the evidence given by these results the Soviet Government started a massive intervention to increase cotton plantations in Central Asia that included the diversion of the two main tributaries of the Aral Sea. In the late sixties the Aral Sea started to shrink. It used to be the fourth largest lake in the world with 67,000 square kilometres in 1960. The surface reduced to 30,000 square kilometres in 1996 with a decline of the average level of water of 16 meters. A disaster that continued with accelerated evaporation, desertification and salinization. The ecosystem of the Aral Sea and the river deltas feeding into it has been nearly destroyed. The receding sea has left huge plains covered with salt and toxic chemicals due to pesticides and fertilizer used in the plantations, which are picked up and carried away by the wind as toxic dust and spread to the surrounding area [Micklin et al., 2008]. This is another case in which there were several contributing factors that hampered the learning process bringing to an illogical behaviour with the repetitions of past failures and mistakes. These included: lack of communication between the different stakeholders interested in the learning process; the complex and very slow chain of the events bringing to the natural damages; the lack of perception of the risk; the high economical revenues from the new plantations; the strong political pressures in favour of such a large and spectacular public intervention.

4. FACTORS AFFECTING THE LEARNING PROCESSES

We have seen in the examples described in the previous Section how the process of learning from feedback and experience is influenced by several factors. Some of these are dependent from the complexity of the learning process, the domain of application and from the explicitness of the learning process and of its goals. Other factors are inherent in the process of learning from experience. We will now see in more detail the most important of these factors discussing the role they could play in masking the evidence coming from past events.

The first factor we are going to consider is the **effectiveness of the learning chain** that is the way in which information about the adverse events, from which one would like to learn, are analysed and transmitted. This is affected by the number of intermediate actors within the learning process, the commitment they have in the process, and the way they perceive the potential consequences of their action. In practical terms bureaucratic processes, involving a lot of people who do not feel the importance of what they are doing, and do not see the benefits of it, bring to less effective results. A good example is the NRLS. The National Patient Safety Agency decided to have a centralised system in which all the information are analysed and remedial actions decided in a central location. The analysts do not have first hand visibility and understanding of the consequences of those decisions, especially considering the specialisation and the lack of standardization and uniformity of the healthcare domain.

Sometimes there are strong **economical, personal or political interests** involved in the process of learning from experience and sometimes these are spread unevenly between the stakeholders involved. For example politicians may act having short or middle terms interest and may be reluctant to embark in unpopular initiatives such as a severe building planning legislation or an effective containment of the green house effect, or other initiatives that may bring results within a long term horizon. In addition, sometimes these initiatives may be opposed by lobbies having strong economical interests and willing to minimise the importance of the past experience. This is the case of the green house effect where some companies try to undermine the importance of early signs of the climate change. An additional important aspect to consider is that sometimes decisions that disregard the past experience are taken by stakeholders who will not be directly influenced by the consequences of those decisions. A typical example is the usage of resources at a rate the experience has shown as non sustainable, and whose exhaustion will impact the future generations.

One of the main differences between the ASRS and the NRLS is that the healthcare world is less uniform as well as less standardised than the aviation one. As a consequence the definition of the negative events and of their severity is much more difficult in healthcare than in aviation. In general, the learning process requires a common agreement around what shall be considered as a negative outcome from a past experience, through the **definition, shared perception and evidence of the mistake** from which one is trying to learn.

If the **link between the potential remedial actions and their expected effect** is not evident or the effect is unsure, the stakeholders may be reluctant to take initiatives that have usually a high cost in economical and organisational terms.

The evidence coming from the past experience is not always easy to understand. In some cases the chain of events and natural changes that can bring to a negative outcome is extremely complex. The depletion of the Ozone layer is a very good example. It took several years to have credible scientific evidence that supported the ozone depletion hypothesis and to move to eliminate the use of CFCs in aerosol spray. Things are even more complex for the global warming, where there are still some controversies about its nature, causes, and consequences. If we look at some of the human caused ecological catastrophes of the past like the Easter island overexploitation and desertification, or the Anasazi deforestation, topsoil erosion, and over population, we realise that these populations were not aware of the natural damages they were producing and not able to interpret the early signs of their negative actions. The ability to learn from experience is then strongly affected by the ability **to catch early signs of the consequences of our mistakes**, at the social, political and economical level and by the presence of **adequate tools to understand these early signs**.

Possible **distortion in risk perception** by society is another important factor in the learning process. Risk is usually defined as the probability of an adverse event multiplied by the magnitude of its consequences and divided by time (Cohen, 1985). However, even if the given definition is useful to define risk at an engineeristic level, it is insufficient and misleading when dealing with people risk perceptions. People have a different conception

of risk, with the magnitude of the consequences having much more importance than probability. In addition, people is prone to a subjective perception of probability, with a tendency to overestimate low probabilities and underestimate intermediate and, especially, high probabilities (Kahneman, 1979). Media have also a strong influence in public perceptions of risk. Studies (Bastide et al., 1989) have shown the tendency to overestimate events associated with dramatic and sensational events with high media coverage (motor vehicle accidents, industrial injuries etc.). These are only a few of the factors that can influence risk perception, that has been the subject of different extensive studies. Some of these studies evidence how the difference between the risk evaluation of the professionals and those of the population is not, or at least not only, due to lack of technical knowledge, misinformation and irrationality. People seem to include in their evaluation several not easily quantifiable factors, using a larger and more complex definition of risks, benefits and acceptability (Kasper, 1980).

5. CONCLUSIONS

This paper used examples of safety critical organisations in aviation and healthcare to discuss the ability to perceive lessons coming from past experience and the risks implied in our current actions and choices. This appears to be influenced by several factors, the most important of which are:

- The number of intermediate steps within the learning process, the commitment of the different stakeholders contributing to the process, and the way they perceive the potential consequences.
- The economical and personal interests touched by the learning process and how these are spread between the stakeholders involved.
- The evidence of the link between the potential remedial actions and their expected effect
- The definition, shared perception and evidence of the mistakes from which one is trying to learn
- The presence of adequate tools to understand, at all levels, the meaning and the importance of some early signs of the consequences of our mistakes.
- The possible distortions in risk perception of our current society

These factors have been briefly analysed and discussed in the paper. The effectiveness of communication and scientific dissemination can be significantly influenced by these factors, that can reduce its possible impact, especially when the target of the dissemination is the society at large, and more effort should be dedicated in analysing how to address these factors when formulating scientific messages.

REFERENCES

- S. J. Bastide, P. Moatti, J. P. Pages and F. Fagnani (1989). "Risk Perception and Social Acceptability of Technologies: The French Case". *Risk Analysis*, Vol. 9, No. 2.
- M. V. Biezma and F. Schanack (2007). "Collapse of steel bridges". *Journal of Performance of Constructed Facilities*, Vol. 21
- C. Billings (1998). "Incident reporting systems in medicine and experience with the aviation reporting system". In R. I. Cook, D. D. Woods & C. Miller (Eds.), *A Tale of Two Stories: Contrasting Views of Patient Safety*.
- I. Carruthers and P. Philip (2006). *Safety First – A report for patients, clinicians and healthcare managers*. UK Department of Health.
- B. Cohen (1985). "Criteria for Technology Acceptability". *Risk Analysis*, Vol. 5, No. 1-3, 1985.

- P. Dallard, P. Fitzpatrick and A. J. Flint (2001). "The London Millennium Footbridge". *Structural Engineer*, 79(22).
- Department of Health (2000). *An Organisation with a Memory: learning from adverse events in the NHS*. Stationary Office, London.
- J. M. Diamond (2005). *Collapse: How Societies Choose to Fail or Succeed*. Penguin Group, New York.
- S. Farrow and H. Hayakawa (2002). "Investing in safety: An analytical precautionary principle". *Journal of Safety Research*, Vol. 33, Issue 2.
- J. Flenley and P. Bahn (2003). *The Enigmas of Easter Island*. Oxford Univ. Press, New York.
- C. W. Johnson (2002). "Reasons for the Failure of Incident Reporting in the Healthcare and Rail Industries". *Proceedings of the 10th Safety-Critical Systems Symposium, Southampton, UK*.
- C. W. Johnson (2004). *Review of the BFU Überlingen Accident Report*. EUROCONTROL, RFQ/137/04.
- D. Kahneman and A Tversky (1979), "Prospect Theory: An Analysis of Decisions under Risk". *Econometrica*, No. 47.
- R. Kasper R (1980). "Perceptions of Risk and Their Effects on Decision Making". In R. Schwing and W. Albers (eds.), *Societal Risk Assessment: How Safe Is Safe Enough ?*, Plenum Press, New York, 1980.
- P. Micklin and N. V. Aladin (2008). "Reclaiming the Aral Sea". *Scientific American*.
- A. Pasquini, S. Pozzi, L. Save and M. A. Sujan (2010). "Requisites for successful incident reporting in resilient organisations". In E. Hollnagel *Resilience Engineering*, Vol. 3.
- H. G. Tyrrell (1911). *History of Bridge Engineering*. Published by the author.

DISCUSSION OF SCENARIOS

Häyhä T., Franzese P. P., Ulgiati S.

REDUCING THE USE OF FOSSIL FUELS: SCENARIOS FOR FINLAND'S ENERGY FUTURE

Krizek K. J. and Marshall J.

MEASURING AND ANALYZING THE SUBSTITUTION EFFECTS OF NON-AUTO TRAVEL AND IMPLICATIONS FOR FOSSIL ENERGY USE: ISSUES, PRESCRIPTIONS, AND EXAMPLES

Jablonska B., Ruijg G. J., Opstelten I. J., Willems E., Epema T.

TRANSITION TO SUSTAINABLE ENERGY NEUTRAL DISTRICTS BEFORE 2050: INNOVATIVE CONCEPTS AND PILOTS FOR THE BUILT ENVIRONMENT

Sagebiel J., Rommel K., Rommel J.

HOW MUCH ARE CONSUMERS WILLING TO PAY FOR IMPROVED AND GREENER ELECTRICITY SUPPLY? RESULTS FROM CHOICE EXPERIMENTS IN HYDERABAD, INDIA

Benes I. and Benesova Z.

CZECH PUBLICS' ATTITUDE TOWARDS ENERGY ISSUES AND TOWARDS THE DESERTEC PROJECT

Diaz Maurin F.

TENTATIVE IDEAS TO EXPLORE THE VIABILITY OF THE NUCLEAR OPTION

Johansson S., Liljequist K., Ohlander L., Aleklett K.

CAN AGRICULTURE PROVIDE US WITH BOTH FOOD AND FUEL?

Viglia S., Gravitis J., Mellino S., Ortega E., Monteiro Souza A. and Ulgiati S.

HOW AND HOW MUCH CAN FOREST ECOSYSTEMS SUPPORT THE PROSPEROUS WAY DOWN?

Cabrera Serrenho A., Sousa T., and Domingos T.

GROWTH MODELS: THE ROLE OF ENERGY

Rathmann R., Szklo A. and Schaeffer R.

MITIGATION POLICIES IN NON-ANNEX I COUNTRIES: IMPACTS ON COMPETITIVENESS OF BRAZILIAN ENERGY-INTENSIVE INDUSTRIES

Ortega E., Ferraz J. M. G., Comar M. V., Odum E. C.

BUILDING UP A PROSPEROUS WAY DOWN IN BRAZIL

REDUCING THE USE OF FOSSIL FUELS: SCENARIOS FOR FINLAND'S ENERGY FUTURE

Tiina Häyhä^{*1,2}, Pier Paolo Franzese², Sergio Ulgiati²

¹ *School of Business and Economics, University of Jyväskylä, Jyväskylä, Finland*

² *Department of Environmental Sciences, Parthenope University of Naples, Naples, Italy*

ABSTRACT

The massive use of fossil energy by modern societies contributes to greenhouse gas emissions and affects ecological and economic systems in many different ways. At the same time, climate change affects energy consumption patterns. Besides climatic factors, energy demand and supply are influenced by economic growth, land use, population growth, technological development, and social trends, among other factors. Energy demand is forecasted to continue growing in the next decades but the supply of fossil fuels on which modern society relies is not unlimited. Such complex situation requires the development of alternative energy scenarios as well as new models of human society based on the sustainable consumption of energy and natural resources. In this study, the main environmental and economic costs of electricity production in Finland were investigated by exploring and correlating economic features (money costs), direct and indirect use of fossil fuels (GER cost), global environmental support (Emergy cost), and environmental impact (CO₂ emissions). Two alternative scenarios for Finland's energy future (year 2025 and 2050) were also drawn and compared with the reference year 2008. The scenario analysis suggests an energy policy for Finland's energy future based on a diversified energy mix oriented to the sustainable exploitation of local, renewable, and environmentally friendly energy sources. In terms of energy security, it would be important to decentralize the energy production and improve energy policies oriented to increase energy efficiency and sustainable energy consumption. Further investigations are still required to better assess the most appropriate energy mix able to minimize both environmental load and economic costs of different technologies of electricity production. Such investigations should always consider the energy return on investment, the economic profitability as well as the environmental sustainability in terms of human health, biodiversity conservation, and integrity of ecosystem functioning.

Keywords: Electricity, Finland, Energy, Emergy, GER, CO₂, Scenario

1. INTRODUCTION

Several scientists have used economic and biophysical accounting methods as a basis for valuing natural resources, human-dominated processes, and man-made ecosystems (Odum, 1988; Costanza et al., 1997; Brown and Ulgiati, 1999; Farber et al., 2002; Patterson, 2002; Franzese et al., 2009a,b). As a complement to "preference-based approaches", biophysical accounting methods use a "cost of production approach", as did some value theories in Classical Economics - e.g., the Ricardian and Marxist embodied labor theory of value - (TEEB, 2010).

Biophysical accounting methods assess value based on the amount of resources invested to produce a product or service, thus resulting particularly useful to assess the environmental performance and sustainability of systems and processes. Biophysical accounting provides an "ecocentric" value of systems and processes complementary to the "anthropocentric" values of Economics. In so doing, it does not aim at replacing economic

* Corresponding author; E-mail: tiina.hayha@uniparthenope.it

values but only to provide additional information from a different point of view, from which public policy might benefit.

The development of national policies to ensure long term energy security and sustainable development is not an easy task. Economic and environmental aspects and constraints of alternative energy scenarios must be properly investigated before the guidelines of an energy policy can be drawn.

A major increase of renewable (biomass and wind) and nuclear power is forecast for Finland's energy future, while fossil fuel-based technologies should decrease over time according to oil price and availability (VTT, 2007, 2009).

In this study, the main environmental and economic costs of electricity production in Finland were investigated by exploring and correlating economic features (money costs), direct and indirect use of fossil fuels (GER cost), global environmental support (Emergy cost), and environmental impact (CO₂ emissions). The performance and sustainability of selected technologies for electricity production were evaluated at plant scale as well as their load at national level. Alternative scenarios for Finland's energy future (year 2025 and 2050) were also drawn and compared with the reference year 2008.

2. MATERIALS AND METHODS

2.1 The Area of Study

Since the early 1970s, Finland has been characterized by an active and successful energy policy. With a total energy consumption of $1.42 \cdot 10^6$ TJ in 2008, Finland uses about half of both primary energy and electricity to supply its industrial sector (VTT, 2007). The Finnish energy system is very diversified, with an energy consumption supplied as follows: oil 25%, wood fuels and hydro power 25%, nuclear power 17%, natural gas 11%, coal 10%, peat 6% (StatFin, 2010).

The total electricity production in Finland in 2008 was 74.5 TWh. Combined Heat and Power plants (CHP plants) were the most significant mode of electricity generation, accounting for 30.3% of the total electricity production. The nuclear power accounted for 25.3%, hydro power 19.3%, condensing power 10.1%, wind power 0.3%. The net import of electricity in 2008 accounted for 15.6% (StatFin, 2010).

While the Finnish hydro power is supposed to be stable in the future having already been exploited at its maximum rate, nuclear, biomass, and wind power could significantly increase over the next 30-40 years (Holtinen, 2007; Rintala et al., 2007; VTT, 2009). Instead, the future dynamics related to fossil fuel-based power plants will be strongly constrained by fuel price and availability as well as the future cost of emission permits (Bentley, 2002; Heinberg, 2009).

2.2 The Economic Cost Analysis

The main aim of Economic Cost Analysis (Layard and Glaster, 1994) is to evaluate the production costs of processes and products. In this paper, the production costs of different technologies for electricity production were calculated on the basis of literature data referring to average size plants in Finland. The costs (referring to the year 2008) were calculated to compare direct costs of electricity production at plant scale and country level according to different scenarios.

Production costs were calculated as the addition of annual investment costs and variable costs including fuel cost, operating and maintenance costs, and emission permits. The annual investment costs were calculated as fixed annual installments, distributing the investment cost over the economic lifetime of the power plant. The annual investment costs were given by the annuity factor calculated as follows:

$$f = r (1+r)^n / (1+r)^n - 1$$

where f is the annuity factor, r is the annual interest rate, and n is the economic lifetime in years. The annual interest rate used was 5.0%.

Carbon emissions released by industries, transportation, and energy production, are considered negative externalities that should be internalized in the production function. European Union began emission trading in 2005 to reach the Kyoto target for CO₂ emissions by 2012. Emission trading increases the production costs of fossil fuel-based technologies according to their emission factors and market price of emission permits. In this study, we assume that emission trading will be applied also in the future leading towards low-emission technologies. In particular, the price of the emission permit, related to direct CO₂ emissions, was assumed to be 25 €/t CO₂ in 2008, 30 €/t CO₂ in 2025, and 40 €/t CO₂ in 2050.

2.3 The Gross Energy Requirement (GER)

According to the International Federation of Institutes for Advanced Study (IFIAS), energy analysis has been defined as the process of determining the energy required directly and indirectly to allow a system to produce a good or service (IFIAS, 1974). The IFIAS conventions were mainly aimed at quantifying the availability and use of fossil fuels stocks (sometimes also referred to as “commercial energy”). In this framework, the GER method accounts for the amount of commercial energy that is required directly and indirectly by the process of making a good or service (Herendeen, 1998a, 1998b). More specifically, it focuses on fuels and electricity, fertilizers and other chemicals, machinery, and assets supplied to a process in terms of the oil equivalent energy required to produce them (Slesser, 1978; Smil, 1991). The GER is expressed in energy units per physical unit of good or service delivered (for instance, MJ per kg of steel). As the GER of a product is concerned with the depletion of fossil energy, all process inputs which do not require the use of fossil and fossil equivalent resources are not accounted for. Resources provided for free by the environment (like for instance topsoil and spring water) are not accounted for by GER method. Human labour and economic services are also not included in most evaluations (Franzese et al., 2009a).

2.4 The Emergy Synthesis

Emergy Synthesis (Odum, 1988, 1996) is an energy evaluation method aimed at calculating indicators of environmental performance and sustainability accounting for both natural and economic resources used up within ecosystems and human-dominated processes (Brown and Ulgiati, 2004; Franzese et al., 2008a,b, 2009a,b; Ulgiati et al., 2010a,b,c).

According to Emergy theory different forms of energy, materials, human labour and economic services are all evaluated on the common basis of biosphere by converting them into equivalents of only one form of energy, the solar kind, expressed as solar equivalent Joule (seJ). To be more specific, emergy is defined as “the total amount of available energy of one kind (most often of the solar kind) that is used up directly or indirectly in a process to deliver an output product, flow, or service” (Odum, 1996). Emergy accounting evaluates the past and present environmental support to a process, exploring the interplay of natural ecosystems and human activities and focusing on what it takes for biosphere to make and for societies to process a given resource. H.T. Odum pointed out that in all systems a greater amount of low quality energy must be dissipated in order to generate a product containing a smaller amount of higher quality energy, in so generating an energy-based hierarchy of resources and products (Odum, 1996).

3. RESULTS AND DISCUSSION

Indicators were calculated considering average size power plants for which an interest rate of 5% and a price of emission permit of 25 €/t CO₂ were assumed. A working time of 8000 hours per year was assumed for coal, natural gas, peat, CHP, and nuclear power

plants while a working time of 2000 hours per year was assumed for wind power. The calculated indicators explored economic features (money costs), direct and indirect use of fossil fuels (GER cost), global environmental support (Emergy cost), and environmental impact (CO₂ emissions).

In Table 1, the indicators of economic and environmental performance per MWh of electricity production are shown. Such multi-disciplinary set of indicators allowed a comprehensive understanding of both economic and environmental features characterizing the different technologies of electricity production. For a better comparison among the different technologies, selected indicators were then normalized and plotted through a radar graph (Figure 1). Peat and coal power plants showed the worst performance in terms of Gross Energy Requirement (4.81 and 4.00 J/J_e, respectively) and CO₂ emissions (1.08 and 1.11 t CO₂/MWh) (Table 1, Figure 1). The high value of the CO₂ emissions for these two technologies also determined the highest monetary cost of the emissions. Wind and hydro power are characterized by a small area (not visible in Figure 1) as they are not supplied by fossil fuels. The use of renewable energy sources for wind and hydro power translates into a lower value of the GER cost, absence of direct CO₂ emissions, and related monetary cost of emissions. Electricity produced by CHP plants was characterized by a production cost of 93 €/MWh, an emission rate of 1.13 t CO₂/MWh, and a cost of emissions of about 18 €/MWh (Table 1). These values are due to the fact that the investigated municipal CHP plants in Finland are supplied not only by wood biomass but instead by a mix of fuels including on average: 37% gas, 24% wood biomass, 20% peat, 19% coal. Gas, peat, and coal fuels are characterized by high CO₂ emissions and related cost of emission permits, lowering the economic and environmental performance of CHP plants (Figure 1).

When in a CHP plant all the production costs are allocated to the electricity production, it seems that such technology does not provide an efficient way to produce electricity. However, the heat co-produced together with electricity generates a considerable income in terms of district heating, lowering the production cost of electricity production.

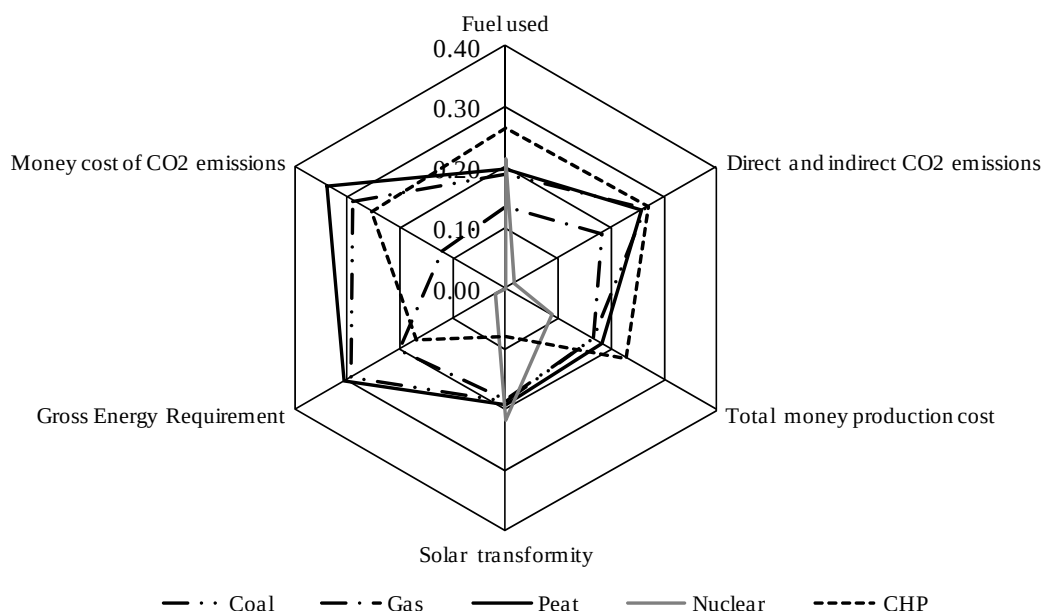


Figure 1. Comparison of economic and environmental indicators showing the performance of selected electricity production technologies per MWh in Finland (year 2008).

According to Tarjanne and Kivistö (2008), we assumed for modern nuclear power plants of 1500 MW a production cost of 35 €/MWh (Table 1). Nuclear electricity is relatively cheap once the reactor is in place and operating. Still, nuclear power plants are extremely costly to build so that unsubsidized nuclear plants are not economically competitive with similar sized fossil fuel plants (Heinberg, 2009).

The solar transformity (emergy per unit energy) showed higher values for nuclear, peat, coal, and gas power plants ($3.36 \cdot 10^5$ seJ/J, $2.99 \cdot 10^5$ seJ/J, $2.87 \cdot 10^5$ seJ/J, $2.86 \cdot 10^5$ seJ/J, respectively) (Table 1). Wind, hydro and CHP plants showed lower value of the solar transformity, highlighting a smaller environmental support needed for such technologies. In particular, according to Buonocore et al. (2010), CHP plants supplied mainly by wood biomass and integrated with wastewater treatment and short rotation coppice can produce electricity with a solar transformity value of $1.22 \cdot 10^5$ seJ/J.

The indicators of economic and environmental load calculated for electricity production at national level in Finland are summarized in Table 2. Figure 2 provides a comparison to better visualize the load at country level generated by the investigated technologies of electricity production. The size of the load is due to both the magnitude of intensity factors and amount of electricity produced by each technology. At country level, CHP and nuclear power plants generated a major economic and environmental load (Figure 2).

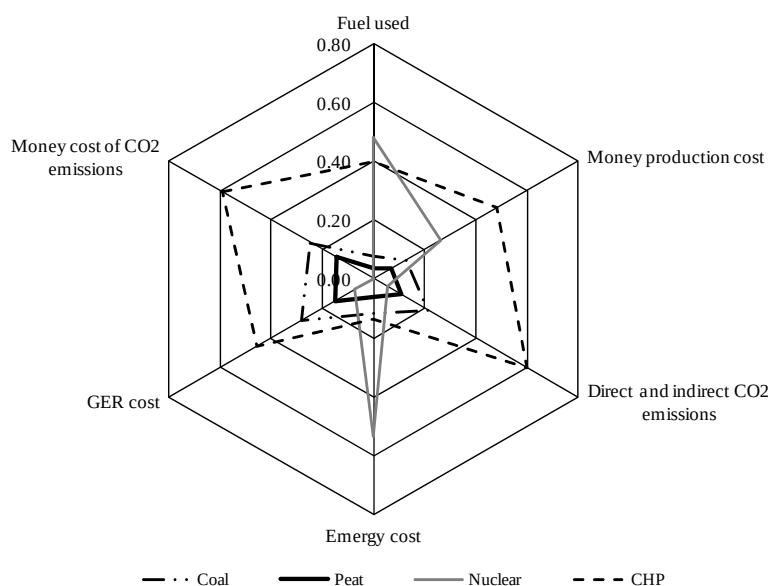


Figure 2. Comparison of economic and environmental indicators showing the load of selected electricity production technologies at national level in Finland (year 2008).

In 2008, the electricity produced by municipal CHP plants accounted for 15.4 TWh while the industrial CHP plants produced 11.1 TWh. In this study, we considered only the electricity produced by municipal CHP plants, accounting for 24% of the total electricity produced by all the investigated technologies. By including also the industrial CHP plants, this value would increase to 30.3% of the total electricity production (StatFin, 2010).

Although hydro power represents an important share of the total amount of electricity produced at country level (19.3%), it generates a low economic and environmental load due to the use of renewable energy. Nuclear power represents 25.3% of the total electricity production while wind power only 0.3% (StatFin, 2010).

Two alternative scenarios for Finland's energy future in 2025 and 2050 are shown in Figures 3 and 4. Scenario 1 was based on a major increase of nuclear power of 13 TWh by 2025 (considering the electricity generated by the power plant under construction "Olkiluoto 3") and a total amount of 39 TWh by 2050 (considering "Olkiluoto 3 and two new modern nuclear power plants as well as the decommissioning of the four old ones). A minor increase of wood biomass and wind power was also assumed in Scenario 1 as well as the retirement of coal, peat, and gas power plants by 2050.

Scenario 2 was based on a remarkable increase of renewable energy sources (mainly biomass and wind power) reaching about 6 TWh of wind power by 2025 and 20 TWh by 2050. Wood biomass was assumed to increase 7 TWh by 2025 and 15 TWh by 2050. In Scenario 2, nuclear power was assumed to be 13 TWh by 2050 (related only to Olkiluoto 3).

In this scenario, coal and gas power plants were assumed to be out of use by 2025 while the use of peat was assumed to be stable over 2025 and double by 2050. The notable increase of wood biomass was assumed to replace the use of coal and gas in CHP plants.

In both scenarios, hydro power was assumed to be stable over time as the maximum utilization of water streams has already been reached and further exploitation is not allowed due to environmental protection and nature conservation policies.

Indicators in Figure 2 were aimed at comparing the load generated by different production technologies at country level. Instead, Figure 3 and 4 were drawn to compare economic and environmental indicators due to different energy mix characterizing Scenario 1 and 2 and the reference year 2008.

Figure 3 shows that the energy mix assumed in Scenario 2 generates a smaller economic and environmental load as all the indicators show smaller figures than in both Scenario 1 and the reference year 2008.

In Figure 4, Scenario 1 shows smaller economic costs and impact in terms of CO₂ emissions as fossil fuels were assumed to be replaced by a massive production of nuclear power. Yet, Scenario 1 shows the biggest value in terms of global environmental support (total Energy cost). Scenario 2 in Figure 4 is negatively affected by doubling the use of peat by 2050 as peat is local and slowly renewable but characterized by high CO₂ emission rate.

Summarizing, Scenario 1 assumed a major increase of nuclear power while Scenario 2 was based on a major increase of renewable energy (mainly biomass and wind power). The first scenario raises several technological problems and environmental concerns for nuclear power, mainly related to safe production and waste disposal, limits of uranium supply availability, and a strong dependence on governmental subsidies, among others. The second scenario also raises some environmental concerns, mainly related to the sustainable exploitation of forest ecosystems to supply massive amounts of wood biomass as well as the real environmental sustainability of peat-based power plants. In both, cases further investigations are required to ensure future energy policies deeply rooted in the principles of sustainable development and able to cope with a post-carbon society (Odum, 2007).

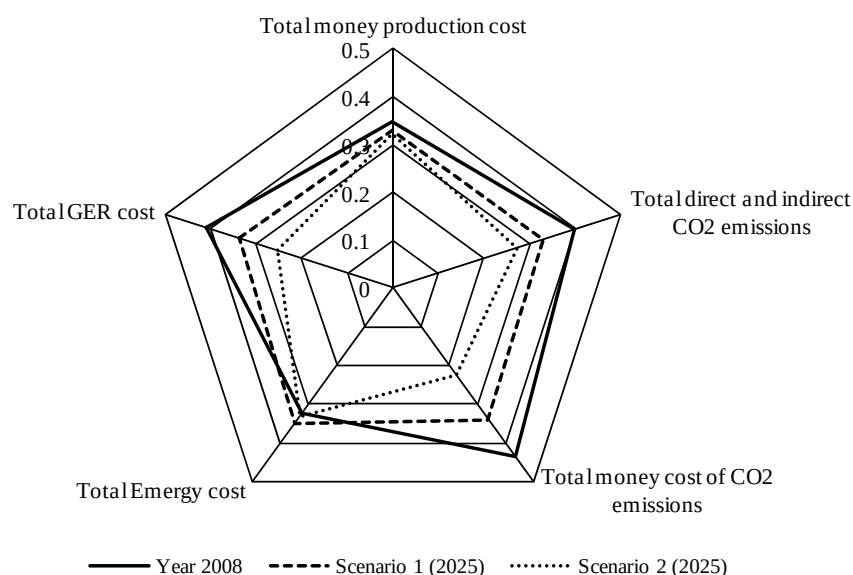


Figure 3. Scenario analysis¹: comparison between the energy mix in 2008 and the Scenarios 1 and 2 drawn for the year 2025.

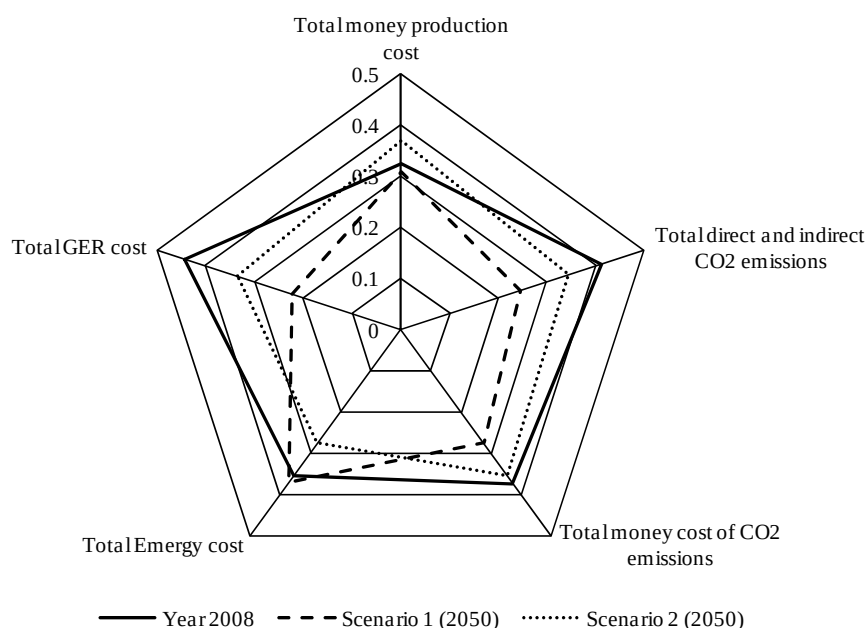


Figure 4. Scenario analysis¹: comparison between the energy mix in 2008 and the Scenarios 1 and 2 drawn for the year 2050.

4. CONCLUDING REMARKS

The most recent energy and climate policy in Finland is aimed at increasing the exploitation of renewable energy sources, stabilising the energy demand, reducing CO₂ emissions, and decreasing the import of primary energy and electricity. Such targets can be reached through alternative energy scenarios according to different economic and environmental trades-off.

In this paper, the main environmental and economic costs of electricity production in Finland in the year 2008 were evaluated. Two alternative scenarios for Finland's energy future were also drawn and compared with the reference year 2008. The scenario analysis suggests an energy policy for Finland's energy future based on a diversified energy mix oriented to the sustainable exploitation of local, renewable, and environmentally friendly energy sources. In terms of energy security, it would be important to decentralize the energy production and improve energy policies oriented to increase energy efficiency and sustainable energy consumption.

Further investigations should be carried out to assess the most appropriate energy mix able to minimize both environmental load and economic costs of different technologies of electricity production. Such investigations should always consider the energy return on investment, the economic profitability as well as the environmental sustainability in terms of human health, biodiversity conservation, and integrity of ecosystem functioning.

Note

1. Since Scenario 1 and 2 were characterized by a slight difference in the total electricity production, indicators in Figure 6 and 7 were divided by the total electricity production and normalized for a better comparison.

Table 1. Economic and environmental indicators showing the performance per MWh of electricity production in Finland (year 2008)

Indicators	Unit	Wind	Ref.	Coal	Ref.	Natural gas*	Ref.	Peat	Ref.	Nuclear	Ref.	Hydro*	Ref.	CHP*	Ref.
Investment cost	€/MWh	650	[9]	163	[9]	88	[9]	188	[9]	344	[9]	-	-	188	[9]
Operating and maintenance costs	€/MWh	11	[2]	8	[2]	5	[2]	8	[2]	10	[2]	6	[7]	8	[6]
Capital costs	€/MWh	52.16	[9]	13.04	[9]	7.02	[9]	15.05	[9]	20.03	[9]	-	-	15.05	[9]
Fuel used	MWh _{fuel} /MWh	n.a.		2.38	[9]	1.72	[9]	2.50	[9]	2.70	[9]	n.a.	n.a.	3.33	[9]
Fuel used	J/MWh	n.a.		8.57E+09	[9]	6.21E+09	[9]	9.00E+09	[9]	9.73E+09	[9]	n.a.	n.a.	1.20E+10	[9]
Fuel cost	€/MWh	-		26.19	[9]	46.35	[9]	27.50	[9]	5.00	[9]	-	-	52.27	[9]
Direct CO ₂ emissions of fuel	t CO ₂ /MWh	-		0.81	[9]	0.34	[9]	0.95	[9]	-		-	-	1.03	[9]
Direct and indirect CO ₂ emissions	t CO ₂ /MWh	0.04	[20]	1.11	[20]	0.76	[20]	1.08	[8]	0.07	[16]	0.01	[20]	1.13	[9]
Money cost of CO ₂ emissions	€/MWh	-		20.27	[9]	8.54	[9]	23.83	[9]	-		-	-	17.75	[9]
Total money production cost	€/MWh	63	[9]	68	[9]	67	[9]	74	[9]	35	[9]	6	[9]	93	[9]
Energy cost of fuel	seJ/MWh	n.a.		5.74E+14	[9]	5.43E+14	[9]	2.86E+14	[9]	2.93E+13	[9]	n.a.	n.a.	6.84E+14	[9]
Solar transformaty of electricity production	seJ/J	1.10E+05	[19]	2.87E+05	[20]	2.86E+05	[20]	2.99E+05	[10]	3.36E+05	[10]	1.12E+05	[19]	1.22E+05	[18]
GER cost of fuel	MJ/MWh	-		5.74E+03	[9]	4.99E+03	[9]	6.78E+02	[9]	3.50E+02	[16]	-	-	1.10E+04	[9]
GER cost per joule of electricity	J/J _e	0.13	[20]	4.00	[20]	2.78	[20]	4.18	[9]	0.26	[16]	0.04	[20]	2.33	[18]

Table 2. Economic and environmental indicators showing the load of electricity production at national level in Finland (year 2008).

Indicators	Unit	Wind	Ref.	Coal	Ref.	Natural gas*	Ref.	Peat	Ref.	Nuclear	Ref.	Hydro*	Ref.	CHP*	Ref.
Total electric power	MW	1.43E+02	[13]	n.a.		7.83E+02	[5]	n.a.		2.65E+03	[5]	3.05E+03	[5]	4.10E+03	[5]
Total amount of electricity produced	MWh/year	2.61E+05	[9]	5.60E+06	[5]	8.00E+05	[5]	2.84E+06	[5]	2.20E+07	[5]	1.69E+07	[5]	1.54E+07	[5]
Total amount of fuel used	J/year	n.a.		3.79E+16	[5]	3.50E+15	[5]	1.84E+16	[5]	2.41E+17	[5]	n.a.	n.a.	1.98E+17	[9]
Total money production cost	€/year	1.65E+07	[9]	3.78E+08	[9]	5.37E+07	[9]	2.11E+08	[9]	7.72E+08	[9]	1.05E+08	[9]	1.43E+09	[9]
Total direct CO ₂ emissions	t CO ₂ /year	-		3.59E+06	[9]	1.93E+05	[9]	1.95E+06	[9]	-		-	-	1.70E+07	[9]
Total direct and indirect CO ₂ emissions	t CO ₂ /year	1.04E+07	[9]	6.22E+09	[9]	6.08E+08	[9]	3.06E+09	[9]	1.54E+09	[9]	1.69E+08	[9]	1.75E+10	[9]
Total money cost of CO ₂ emissions	€/year	-		1.14E+08	[9]	6.83E+06	[9]	6.76E+07	[9]	-		-	-	2.74E+08	[9]
Total energy cost of fuel used	seJ/year	n.a.		2.54E+21	[9]	3.06E+20	[9]	5.85E+20	[9]	7.24E+20	[9]	n.a.	n.a.	1.13E+22	[9]
Total energy cost of electricity production	seJ/year	1.03E+20	[9]	5.79E+21	[9]	8.23E+20	[9]	3.06E+21	[9]	2.67E+22	[9]	6.82E+21	[9]	6.77E+21	[9]
Total GER of fuel used	MJ/year	-		3.22E+10	[9]	3.99E+09	[9]	1.92E+09	[9]	7.72E+09	[9]	n.a.	n.a.	1.69E+11	[9]
Total GER of electricity production	J/year	1.23E+14	[9]	8.07E+16	[9]	8.00E+15	[9]	4.26E+16	[9]	2.06E+16	[9]	2.56E+15	[9]	1.29E+17	[9]

Appendix A – Notes in Tables 1, 2, and 3.

* Combined cycle. * The capital costs of old hydropower plants have been already paid back and therefore the production cost of hydro electricity is given only by the addition of operating and maintenance costs. - Not present. # Public (not industrial) CHP plants use a different fuel mix, mainly including gas, wood biomass, peat, and coal.
N.a. = not available.

Appendix B – Reference to literature in Tables 1, 2, and 3.

[1] GreenStream Network, 2007. [2] Tarjanne and Kivistö, 2008. [3] Energiamarkkinavirasto, 2010. [4] Puuenergia, 2010 (fuel price 2009). [5] StatFin, 2010. [6] Our assumption based on literature data. [7] IEA and NEA, 2005. [8] Our calculation based on IPCC, 2006. [9] Our calculations based on literature data. [10] After Odum, 1996. [11] Bargigli et al., 2004. [12] Lapp, 1991. [13] Holttinen and Stenberg, 2009. [14] Hagström, 2006. [15] Boustead and Hancock, 1972. [16] Our calculation based on Sovacool, 2008. [17] Biondi et al., 1989. [18] Buonocore et al., 2010. [19] Brown and Ulgiati, 2004. [20] Brown and Ulgiati, 2002.

REFERENCES

- [1] Bargigli, S., Rauei, M., Ulgiati, S., 2004. "Comparison of thermodynamic and environmental indexes of natural gas, syngas and hydrogen production processes". *Energy*, 29: 2145-2159.
- [2] Bentley, R.W., 2002. "Global oil & gas depletion: an overview". *Energy Policy*, 30: 189-205.
- [3] Biondi, P., Panaro, V., Pellizzi, G., 1989. *Le richieste di energia del sistema agricolo italiano*. CNR, Consiglio Nazionale delle Ricerche, Progetto Finalizzato Energetica, Sottoprogetto Biomasse ed Agricoltura, Report LB-20, Roma, Italia, 389 pp. (In Italian).
- [4] Boustead, I., Hancock, G.F., 1979. *Handbook of industrial energy analysis*. John Wiley & Sons, New York, 422 pages.
- [5] Brown, M.T., Ulgiati, S., 1999. "Emergy evaluation of the biosphere and natural capital". *AMBIO*, 28: 486-493.
- [6] Brown, M.T., Ulgiati, S., 2002. "Emergy evaluations and environmental loading of electricity production systems". *Journal of cleaner production*, 10: 321-334.
- [7] Brown, M.T., Ulgiati, S., 2004. *Emergy analysis and environmental accounting. Encyclopedia of Energy*, volume 2.
- [8] Buonocore, E., P.P. Franzese, T. Rydberg, S. Ulgiati, 2010. "Emergy evaluation of an integrated bioenergy production system. The case study of Enköping (Sweden)". In: Brown M.T., Campbell D., Comar V., Haung S.L., Rydberg T., Tilley D., Ulgiati S. (Eds.), *EMERGY SYNTHESIS 6. Theory and Applications of the Emergy Methodology*. H.T. Odum Center for Environmental Policy, University of Florida, Gainesville, Florida, USA, January 12, 2009. Accepted for publication. In Press.
- [9] Costanza R., d'Arge R., de Groot R., Farber S., Grasso M., Hannon B., Limburg K., Naeem S., O'Neill R. V., Paruelo J., Raskin R. G., Sutton P., van den Belt M., 1997, "The value of the world's ecosystem services and natural capital", *Nature* 387: 253 – 260.
- [10] Energiamarkkinavirasto, 2010.
http://www.energiamarkkinavirasto.fi/data.asp?articleid=1842&pgid=188*
Last access 27 August 2010.
- [11] Farber, S.C., Costanza, R., Wilson, M.A., 2002. "Economic and ecological concepts for valuing ecosystem services". *Ecological Economics*, 41: 375-392.
- [12] Franzese, P.P., Russo, G.F., Ulgiati, S., 2008a. "GIS and Emergy Synthesis evaluation of urban waste management". In: Barbir, F. and Ulgiati, S. (Eds.), *Sustainable Energy Production and Consumption. Benefits, Strategies and Environmental Costing*. NATO Series: Science for Peace and Security, pp. 339-352. Springer. (ISBN: 978-1-4020-8493-5; ISSN 1871-4668).
- [13] Franzese, P.P., Russo G.F., Ulgiati S., 2008b. "Modeling the interplay of environment, economy and resources in marine protected areas. A case study in Southern Italy". *Ecological Questions*, 10: 91-97.
- [14] Franzese, P.P., Rydberg T., Russo G.F., Ulgiati S., 2009a. "Sustainable biomass production: a comparison between Gross Energy Requirement and Emergy Synthesis methods". *Ecological Indicators*, 9: 959-970.
- [15] Franzese P.P., S. Arico, S. Viglia, G.F. Russo, S. Ulgiati, 2009b. "Emergy-based evaluation of natural capital and ecosystem services: the case study of Astroni Wildlife Reserve, Italy". In: Brown M.T., Campbell D., Comar V., Haung S.L., Rydberg T., Tilley D., Ulgiati S. (Eds.), *EMERGY SYNTHESIS 5. Theory and Applications of the Emergy Methodology*. Center for Environmental Policy, University of Florida, Gainesville, USA, pp. 55-64 (ISBN: 978-0-9707325-4-5).
- [16] GreenStream Network, 2007. *Selvitys uusiutuvan energian lisäämisen kustannuksista ja edistämiskeinoista*. Raportti Energiateollisuus ry:lle. (In Finnish).

- [17] Hagström, P., 2006. *Biomass Potential for Heat, Electricity and Vehicle Fuel in Sweden*. PhD thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden.
- [18] Heinberg, R., 2009. *Searching for a Miracle. "Net Energy". Limits & the Fate of Industrial Society*. A joint project of the International forum on Globalization and the Post Carbon Institute, 76 pp.
- [19] Herendeen, R., 1998a. *Ecological Numeracy: Quantitative Analysis of Environmental Issues*. John Wiley and Sons, 360 pp.
- [20] Herendeen, R., 1998b. "Embodied energy, embodied everything... now what?" In: Ulgiati, S., Brown, M.T., Giampietro, M., Herendeen, R.A. and Mayumi, K. (Eds.), *Book of Proceedings of the International Workshop Advances in Energy Studies. Energy Flows in the Ecology and Economy*, Porto Venere, Italy, May 26/30, 1998, pp. 13–48.
- [21] Holttinen, H. 2008. *Statistics of wind power production. Yearbook 2007*. VTT working papers: 106. (In Finnish).
- [22] Holttinen, H., Stenberg, A., 2009. *Wind power production statistics. Report 2008*, VTT. (In Finnish).
- [23] IEA and NEA, 2005. *Projected costs of Generating electricity 2005 Update*.
- [24] IFIAS, 1974. *Energy analysis*. Workshop Report no. 6. Stockholm, 89 pp.
- [25] IPCC, 2006. <http://www.ipcc.ch/pdf/activity/2006gls-brochure.pdf> Last access 27 August 2010.
- [26] Lapp, 1991. C.W. Lapp, *Energy analysis of the nuclear power system in the United States*. In: MS Paper, Department of Environmental Engineering Sciences, University of Florida (1991).
- [27] Layard, R., Glaister, S., 1994. *Cost-benefit analysis*, 2.nd edition. Cambridge University Press 1994.
- [28] Odum, H.T., 1988. "Self-organization, transformity, and information". *Science*, 242: 1132–1139.
- [29] Odum, H.T., 1996. *ENVIRONMENTAL ACCOUNTING. Emery and Environmental Decision Making*. John Wiley & Sons, New York, USA, 370 pp.
- [30] Odum, H.T., 2007. *Environment, Power and Society for the Twenty-First Century: The Hierarchy of Energy*. Columbia University Press, USA, 432 pp.
- [31] Patterson, M.G., 2002. "Ecological production based pricing of biosphere processes". *Ecological Economics*, 41: 457-478.
- [32] Puuenergia, 2010. <http://www.puuenergia.fi/> Last access 27 August 2010.
- [33] Rintala, J., Alen, R., Lahti-Nuuttila, T., Lund, P., Nyrönen, T., Pietola, K., Sipilä, K., Turpeinen, H. ja Helynen, S., 2007. *Arvio biomassan pitkän aikavälin hyödyntämismahdollisuuksista Suomessa*. Asiantuntijatyöryhmän raportti KTM:lle. (In Finnish).
- [34] Slessor, M., 1978. *Energy in the Economy*. Macmillan, London.
- [35] Smil, V., 1991. *General Energetics: Energy in the Biosphere and Civilization*. John Wiley and Sons, New York, USA, 369 pp.
- [36] Sovacool, B.K. "Valuing the greenhouse gas emissions from nuclear power: A critical survey". *Energy Policy*, 36:2940-2953.
- [37] StatFin, 2010. *Preliminary Energy Statistics 2009*. http://www.stat.fi/til/ehkh/2009/04/ehkh_2009_04_2010-03-24_tau_012.xls Last access 30 August 2010.
- [38] Tarjanne, R., Kivistö, A., 2008. *Comparison of electricity generation costs*. Lappeenranta University of Technology. Research report B-175. ISBN: 978-952-214-543-7. (In Finnish).
- [39] TEEB, 2010. *The economics of valuing ecosystem services and biodiversity*. Chapter 5.
- [40] Ulgiati S., Zucaro, A., Franzese, P.P., 2010a. "Shared Wealth or Nobody's Land? The Worth of Natural Capital and Ecosystem Services". *Ecological Economics*. Accepted for publication. In press.
- [41] Ulgiati, S., M. Ascione, S. Bargigli, F. Cherubini, M. Federici, P.P. Franzese, M. Raugei, S. Viglia, A. Zucaro, 2010b. "Multi-method and multi-scale analysis of energy and resource conversion and use". In: Barbir, F. and Ulgiati, S. (Eds.), *Energy Options Impacts on Regional Security*. Book of the NATO Series: Science for Peace and Security, Springer. Accepted for publication. In Press.
- [42] Ulgiati, S., Ascione M., Bargigli S., Cherubini F., Franzese, P.P., Viglia, S., Zucaro, A., 2010c. "Material, Energy and Environmental Performance of Technological and Social Systems under a Life Cycle Assessment Perspective". *Ecological Modelling*. Accepted for publication. In press.
- [43] VTT, 2007. *Energy use. Visions and Technology Opportunities in Finland*. Edita.
- [44] VTT, 2009. *Energy visions 2050*. Edita.

MEASURING AND ANALYZING THE SUBSTITUTION EFFECTS OF NON-AUTO TRAVEL AND IMPLICATIONS FOR FOSSIL ENERGY USE: ISSUES, PRESCRIPTIONS, AND EXAMPLES

Kevin John Krizek^{*1} and Julian Marshall²

¹ *University of Colorado, USA*

² *University of Minnesota, USA*

ABSTRACT

As concerns of climate change increase, the transportation sector is seen as a major, and increasing, contributor. The US currently accounts for about 33 percent of world CO₂ emissions from road transport, largely owing to household vehicle use. Strategies to reduce vehicular emissions are threefold: (1) employing lower carbon-content fuels, (2) using more fuel efficient vehicles, and (3) lowering levels of vehicular use and spurring use of non-motorized modes of transport. The first two rely largely on technical remedies. The latter involves behavioral changes and directly relate to the urban planning profession. For example, city-wide campaigns argue that increased bicycling and walking save gas and improve city air quality; Internet mapping applications calculate emissions savings from walking or cycling trips.

To date, environmental and transportation researchers have primarily employed guesswork as to which non-motorized trips substitute for automobiles trips and thus produce energy savings. Some environmental advocates claim that all non-motorized trips substitute for a transit or automobile trip. At the other end of the spectrum are non-motorized trips for recreation, which most analysts agree do not substitute for auto trips.

This research identifies and evaluates alternative approaches to measuring substitution and uncovers, for the first time, reliable estimates of the fossil fuel reductions from these modes. After introducing a typology of different types of travel substitution behaviors (e.g., non-motorized for driving, ICT for driving), we review different approaches that have been used by analysts to account for or measure the substitution effect.

The final section reports "proof of concept" survey efforts to illustrate dimensions of how non-motorized substitution travel could conceivably be accounted for. Using non-random samples from several urban and suburban settings in Denver (Colorado), we conducted administered assisted surveys to glean various and detailed aspects of non-motorized travel. Between all survey sights, we specifically captured important characteristics for more than 400 non-motorized travelers to uncover rates of vehicular substitution behavior. The results allow us to comment on the degree to which non-motorized travel substitutes for vehicular travel by geographic setting, trip purpose, socio-demographics, and other. We then translate these substitution benefits into energy savings. The findings allow policy analysts and other interested parties a methodology to estimate the degree to which efforts to spur walking and cycling address concerns of climate change and breaking the addiction to fossil energy.

Keywords: climate change, transportation, travel behavior, carbon emissions, substitution, walking, cycling, surveys, measurement

* Presenting Author: Kevin John Krizek (krizek@colorado.edu)

TRANSITION TO SUSTAINABLE ENERGY NEUTRAL DISTRICTS BEFORE 2050: INNOVATIVE CONCEPTS AND PILOTS FOR THE BUILT ENVIRONMENT

*Jablonska, B.*¹, Ruijg, G.J.¹, Opstelten, I.J.¹, Willems, E.², Epema, T.³*

¹ *ECN, The Netherlands*

² *Cauberg-Huygen Consulting Engineers (CHRI), The Netherlands*

³ *TNO, The Netherlands*

ABSTRACT

The Dutch project 'Transition in Energy and Process for a Sustainable District Development' focuses on the transition to sustainable, energy neutral districts in 2050, particularly in energy concepts and decision processes.

The main objective of the technical research is to develop four to six innovative energy concepts for 2050 for the four Dutch cities of Almere, Apeldoorn, Nijmegen and Tilburg, as well as the roadmap for realising this target.

Firstly, 14 variations of six general energy concepts have been developed and calculations conducted on the energy neutrality in 2020, 2035 and 2050 by means of an Excel model designed for this purpose.

Three concepts are based on the idea of an energy hub (smart district heating, cooling and electricity networks, in which generation, storage, conversion and exchange of energy are all incorporated): the geo hub (using waste heat and/or geothermal energy), the bio hub (using waste heat and/or biomass) and the solar hub (using only solar energy). The fourth concept is the so-called all-electric concept, based predominantly on heat pumps, PV and conversion of high temperature heat from vacuum collectors to electricity. The fifth concept uses only conventional technologies that have been applied since the second half of the previous century, and the sixth one uses only hydrogen.

Calculations show that by implementing the hub concepts, the energy neutrality in 2050 ranges from 130 % (solar hubs) to 164% (geo hubs), excluding personal transport within the district.

With the all-electric concept, an energy neutrality of 157% can be reached. Hydrogen only and Conventional concepts perform worse, but nevertheless reach an energy neutrality of around 115% in 2050.

The energy neutrality shows the extent to which a district, in which the given concept is implemented, can supply itself with sustainable energy generated within the boundaries of that district.

Based on the six general concepts, the most optimal energy concepts tailored for the involved four cities have been drawn up and elaborated as pilots, in close cooperation with the representatives of the involved municipalities.

The research up to now has shown that it is possible to realise energy neutrality in 2050 by implementing innovative technical concepts on district level. In this approach, different districts have different sustainable energy potentials that have their peak supply at different times. The smart approach therefore is not the autarkic district, but an exchange of surplus sustainable energy with neighbouring districts and import of the same amount of energy in case of a shortage.

Keywords: energy neutrality, district, energy concept, energy hub, all-electric

1. INTRODUCTION

To many of us the year of 2050 seems too far away to be occupied with it. Nothing could be further from the truth! Certainly not if we wish to break our addiction to fossil fuels

* Corresponding author; E-mail: Jablonska@ecn.nl; Tel.: +31-224-568130

and aim at living in energy neutral neighbourhoods in 2050. To reach this future vision, we need to take certain steps today, develop innovative and integral energy concepts for renovation and new housing and apply them to entire districts.

One third of the current Dutch (and European) energy demand comes from the built environment. A characteristic of the built environment is that it changes very slowly. Each year, 1% of new buildings is added to the existing building stock. The buildings constructed now will still be here 50 years later.

The target of the Dutch government, in accordance with the European targets, is to reach 20% renewable energy supply in 2020 [PEGO, 2009]. The document [New Energy for the Netherlands, 2009] contains a plea of the leading political parties in favour of a completely renewable energy supply in 2050.

The innovative energy concepts can contribute to these targets. Moreover, the progressive municipalities hold a tool in their hands that can be used to realise their energy visions in the long term.

2. ENERGY NEUTRAL DISTRICT

An energy neutral district, as defined in this project, does not have to follow the municipality boundaries and consists of a mix of residential and commercial buildings. It is assumed that the energy for industry and transport other than personal transport is generated outside the district boundaries. Furthermore, the agricultural areas and energy sources from outside the district, such as wind turbines (for example offshore) and biomass (forests, agricultural sources), are excluded.

One exception is waste heat from large-scale incineration and combustion plants, which process mainly waste from the district such as domestic and company refuse.

A district is energy neutral if, on a yearly base, no net energy import is necessary from outside the district. An energy neutral district is not an autarkic district that does not exchange any energy with its surrounding districts. Surplus of energy can be exported and, in case of energy shortage, the same amount of energy can be imported from the surrounding districts. It is better to import or export electricity than to store it.

3. TRIAS ENERGETICA

The design of energy neutral districts follows the three steps of the Trias Energetica, while the need of energy storage, exchange and conversion is emphasized. The Trias Energetica for energy neutral districts can be detailed in five steps:

1. Limit energy consumption
2. Use renewable energy optimally
3. Exchange energy in energy hubs and in smart grids
4. Buffer energy on day, week and season scales in order to match the demand and supply of renewable energy
5. Use imported energy and fuel efficiently in case of shortage in renewable energy generation, and in case of emergency.

In Figure 1 below, the Trias Energetica for energy neutral districts is represented in five steps. All of these five steps are equally important and should be considered in any innovative energy concept.

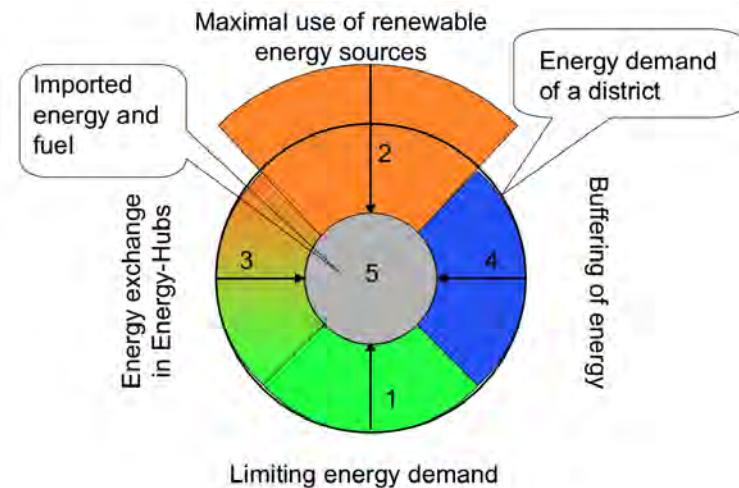


Figure 1. Trias Energetica for development of energy neutral districts in five steps [Willems, 2010]

4. FUTURE ENERGY HOUSEKEEPING

The starting point for establishing the energy demand of the innovative concepts in 2050 is based on the so-called Building Future Potential Study 2050 [Koene et al; 2008] and [Visser, et al; 2009]. According to this study, the main features of the energy system in 2050 are as summarized below (Figure 2):

- The energy demand of a district can be broken down in the energy demand of:
 - Buildings
 - Transport in the district and
 - The surroundings of the buildings in that district.
- Due to a far-reaching reduction of demand in 2050, the total average energy demand of a house will be approximately 33 GJ annually, broken down in:
 - o Hot water (4.5 GJ or 185 m³ gas annually)
 - o Space heating (6.5 GJ or 300 m³ gas annually)
 - o Electricity (9 GJ or 2,450 kWh annually)
 - o Electricity demand outside buildings (0.3 GJ annually)
 - o Cooling demand (1.6 GJ or 300 kWh_e annually) and
 - o Personal transport (11 GJ annually).

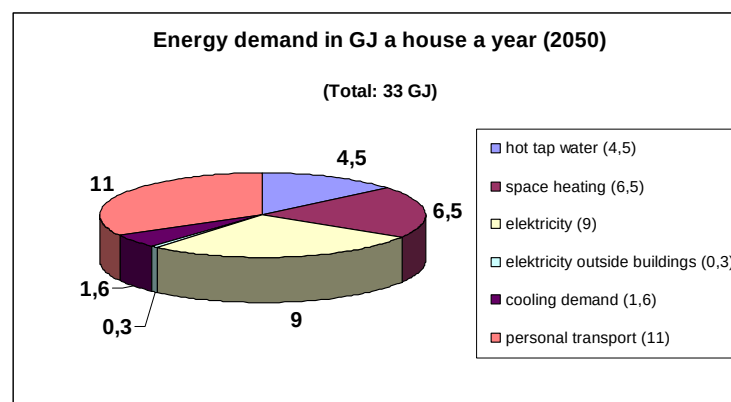


Figure 2. Annual energy demand of a house in GJ, assessed for 2050 [ECN, 2009]

5. TECHNOLOGIES OF THE FUTURE

Renewable technologies that can be deployed in innovative energy concepts can be classified as existing, future (within app. 10 years) and still to be developed technologies (after 2020).

Existing renewable technologies comprise of high and low temperature district heating networks, geothermal sources, heat and cold storage, flat plate and vacuum tube solar collectors, heat pumps, heat-driven cooling, PV (photovoltaic modules), urban wind energy and biomass. The future renewable technologies are, among others, organic rankine cycle (ORC), heat pump booster, electricity hub, heat and power matcher, compact season heat storage and hydrogen as an energy carrier. Still to be developed renewable technologies are, among others, bi-directional district heating networks, heat hub and energy hub.

6. ENERGY HUBS

An energy hub is a central point in a district where all energy distribution systems meet each other and energy flows can be converted. Vehicles can be refuelled with (bio)gas or liquid biofuel there, for example. (Bio)gas can be used for combined heat and power systems in order to generate heat and electricity. Electricity can be used to charge electric vehicles and to generate heat or cold with heat pumps. Energy hubs will probably be equipped with seasonal storage of heat and cold. Energy management, based on the PowerMatcher™ (Figure 3) and HeatMatcher (under development) technology will be used to coordinate the generation, supply and demand of all energy flows and conversions. The energy hub makes sure that the entire renewable energy generation potential of all connected systems will be exploited to its maximum.



Figure 3. Supply and demand matching with the PowerMatcher™ [ECN, 2009]

7. DEGREE OF ENERGY NEUTRALITY

The performance of innovative energy concepts has been calculated in an Excel model. The energy performance is expressed in terms of “degree of energy neutrality” (or energy self-sufficiency). The degree of energy neutrality is defined as the renewable energy generated in a district, divided by the energy demand of that district. If the degree of energy neutrality is higher than 100%, this means that the district can export energy surplus. Values under 100% mean that the district needs to import renewable (or fossil) energy in order to meet its energy demand.

8. ENERGY CONCEPTS FOR 2050

Six types of energy concepts on a district scale have been developed by means of well considered combinations of the above mentioned technologies:

1. Geo hubs
2. Bio hubs
3. Solar hubs
4. All-electric
5. Conventional concepts and
6. Hydrogen concepts

Within these six general concepts, 14 variations have been elaborated. The energy performance, which is expressed as the degree of energy neutrality, has been calculated for each concept variation for the years 2020, 2035 and for 2050.

The first step in all energy concepts consists of limiting the energy demand by means of building or renovating according to the passive house standard. Newly built buildings reach the passive house standard by an excellent building envelope (insulation and air tightness), low temperature space heating and heat recovery from ventilation air. The heat demand for newly built passive dwellings is 15 kWh/m² of floor area annually. Renovated houses have a higher heat demand: 28 kWh/m² of floor area annually. Both types of houses also have heat recovery from waste water.

The average roof area suitable for solar energy generation systems such as solar collectors, PV and PVT (combined solar collector and PV) will increase in time up to 28.1 m² per dwelling. The increase of the available roof area is mainly due to the increasing southern orientation of the buildings.

The energy concepts have been summarized in Table 1 below.

ENERGY CONCEPTS			Degree of energy neutrality [%]					
			2020		2035		2050	
1	Waste Heat and/or Geothermy (Geo-Hubs)	Individual or collective	Cooling		Transport			
			excl	incl	excl	incl	excl	incl
	High temperature waste heat utilization or geothermy	District heating	96	61	120	73	164	96
2	Waste Heat and/or Biomass (Bio-Hubs)	District heating	93	60	119	72	163	95
3	All-Solar concepts (Solar-Hubs)	District heating	53	34	73	45	130	76
	High temperature storage of solar heat		47	30	72	43	131	76
	Low temperature storage with ORC or heat pumps							
4	All-Electric concepts	Individual	71	45	102	61	150	87
	Individual electric heat pumps, PV and solar collectors		73	47	106	64	157	92
	Individual electric heat pumps and PV							
5	Conventional concepts with PV	Individual	36	23	64	38	112	65
	Individual gas boilers with PV		38	24	65	40	114	67
	Individual gas boilers, solar collectors and PV							
6	Hydrogen concepts	Individual	15	7	57	30	115	54

Table 1. Degree of energy neutrality of the concepts in 2020, 2035 and 2050 [ECN]

In 2050, all concepts can reach full energy neutrality, unless personal transport in the district is included.

9. PILOTS IN FOUR DUTCH CITIES

The above mentioned general energy concepts serve as a blueprint for the selection of specific energy concepts for the participating municipalities. The choice depends on several aspects such as the district features, availability and type of energy sources, characteristics of the existing buildings and the infrastructure, size of the district and the energy visions of the municipalities. After all, the economy of an energy concept will often be the decisive aspect in the selection of a concept.

9.1 City of ALMERE - The Kruidenwijk

The Kruidenwijk residential area, located in the Northwest of the city of Almere, is characterized by low-rise buildings from the 1980s (Figure 4). The Noorderplassen lake can be found north of the residential area. The lake is approximately 20 meters deep and is used as a well for extracting sand. The houses have predominantly flat roofs and more than half of the houses is oriented to the south. Facades can be easily upgraded to the passive house standard.

There is a district heating network with high temperature heat in the Kruidenwijk. The network also extends to other districts in the city.

Because of the existing district heating network and the Noorderplassen, energy concept 1 (high temperature geothermal heat) with a possible contribution of biomass (concept 2) has been selected for the Kruidenwijk district. If geothermal energy is proven to be unfeasible, then concept 3 (low temperature storage in the Noorderplassen lake with ORC) and/or heat pumps is preferred.



Figure 4. An example of dwellings in the Kruidenwijk residential area [Ymere]

9.2 City of APELDOORN - The Kanaalzone Noordoost

The Roadmap 2020 [Apeldoorn is bursting with energy; 2009], amended in 2010, expresses the aspiration of Apeldoorn to become 100 % energy neutral in 2035. The Apeldoorn municipality aims at an all-electric concept with small-scale district heating networks if needed.

The Kanaalzone Noordoost will be restructured until 2025 [Masterplan Kanaalzone Noordoost, 2009]. The district is characterized by a mix of existing buildings, newly built housing and small-scale industry. A part of the Kanaalzone Noordoost will serve as a recreational area. A channel flows through the whole district. The present industrial buildings will be replaced by offices and dwellings. The Apeldoorn municipality strives for a combination of living and working while the small-scale character and cultural, historical and natural values will be preserved.

Biomass and domestic refuse will not be used directly as an energy source in the district, but will be transported to the biogas generation units outside the district. The biogas will be upgraded to natural gas quality and transported back to the city where it will be converted into heat and electricity in combined heat and power installations on biogas. The ground of Apeldoorn is probably suitable for generation of renewable heating and cooling energy. The remaining cooling demand is expected to be low (contrary to offices, passive houses have no significant cooling demand) and can be generated by heat and cold storage in the groundwater. Heat can be generated by electric heat pumps (ORC in winter mode).

To be able to use the channel in Apeldoorn for generation of heating or cooling it is necessary that the water flows sufficiently. At present, the channel water is nearly stagnant but it can be made to flow. This can be achieved by pumping the water up and

letting it flow back into the channel at certain locations outside the district that have the required level differences.

In view of the aspiration of the Apeldoorn municipality and the Kanaalzone Noordoost characteristics, concept 4 (all-electric) combined with concept 3 (low temperature storage with ORC or heat pumps) seem to be the most suitable option (Figure 5).

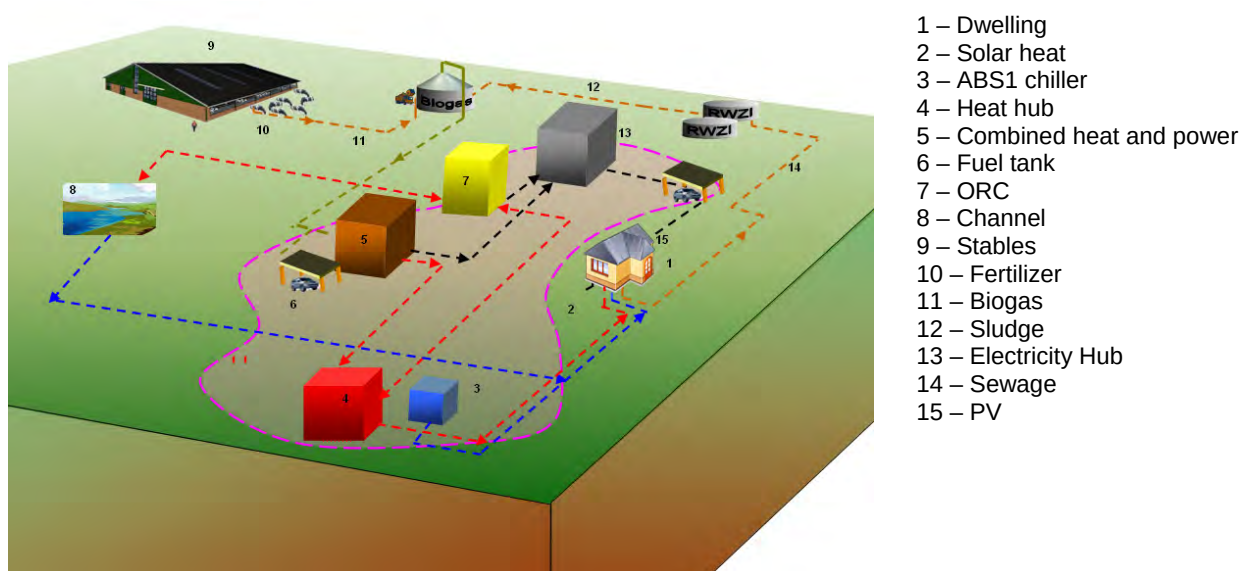


Figure 5. Energy flows in the Kanaalzone Noordoost area

9.3 City of NIJMEGEN - Waalfront, Waalsprong and the city centre

The Waalsprong is a residential area with 8,500 low-rise houses built early in the 21st century, north of the river Waal and opposite the city centre. The Waalfront is a former industrial area west of the city centre and at the south bank of the Waal, where approximately 2,650 houses will be built. Many houses in the city centre are up for renovation.

These three locations together can become energy neutral in 2050. The new housing in the Waalsprong and Waalfront areas will have a net energy surplus, providing the city centre with energy. Because of the existing and especially historical buildings, and relatively small roof area for renewable energy generation it seems improbable that the city centre itself could become energy neutral.

The Nijmegen municipality has the aspiration to achieve energy neutrality in the Waalsprong by implementing a hybrid district heating network [Roos et al; 2009].

In the near future, a bypass of the river Waal will be realised, thus creating two islands. The river Waal can be used for cooling and for generating energy from the flow. The cold will be used mainly in offices.

An aquifer supplies cold that can be directly used for cooling of buildings. Heat can be generated from the aquifer by electric heat pumps.

A geothermal source built as a doublet offers a possibility for extracting high temperature heat. This doublet can serve as a temporary storage for excess high temperature heat, including solar heat generated by vacuum tube solar collectors.

The waste treatment plant in the district also supplies heat (40-50°C) that is not at the expense of the electrical efficiency. The coal- and partly biomass-fuelled Electrabel G13 power plant supplies waste heat to companies in its vicinity. The G13 will be closed down in 2035.

Because waste heat is available in Nijmegen and there are enough possibilities for generating geothermal and solar energy, and due to the river Waal, concepts 1 or 2 have been selected (geo hub or bio hub with moderate temperature waste heat utilisation). A

combination with concept 3 (solar hub with high temperature central storage of solar heat) is possible.

9.4 City of TILBURG - Tilburg North

Tilburg North will be re-developed until 2020. The extensive maintenance of approximately 1,100 houses (year of construction is 1965-1970) has been planned for the near future. At the same time, a new housing development of 700-800 houses will be realised at the north side of the city.

The largest part of the city has a district heating network. The high temperature network is fed by the waste heat from the coal-fuelled Amer power plant.

The aspiration of the Tilburg municipality is to become energy neutral in 2045. One of the main targets is making the existing district heating network as energy-efficient and environmentally friendly as possible. The Tilburg municipality also intends to realise large scale heat and cold storage.

If the Amer power plant closes down, the solar collectors and combined heat and power plants on biogas, possibly combined with geothermal heat, can feed the district heating network. Heat storage will take place by means of compact thermo-chemical heat storage applied in the houses and/or by geothermal doublets. In principle, electricity storage will not take place in the energy hub, but in the batteries of electric vehicles. Vehicles will be connected to the electricity grid of houses and other buildings. This is feasible due to the so-called Vehicle-to-Grid system (V2G, under development). Electricity that cannot be stored this way can be exchanged with the rest of Europe.

The city of Tilburg has the ambition to upgrade the district heating network in an energy-efficient and environmentally friendly system and since there are enough renewable energy sources that enable the continuation of this network, the energy hub concept is suitable. In the district, a transition from concepts 1 or 2 (geo or bio hub with high temperature waste heat utilisation, using biomass) to concept 3 (solar hub with high temperature storage of solar heat) will take place.

10. CONCLUSIONS

Based on the conducted research the following conclusions can be drawn:

- Energy neutrality of the built environment can only be reached by an extensive reduction in energy demand. Sun oriented new buildings and new and renovation building development according to the passive house standard, and development of high-performance heat recovery from waste water are essential.
- In 2050, energy neutrality is feasible with all the elaborated concepts. The geo and bio hubs and the all-electric concepts lead to the highest degree of energy neutrality, followed by solar hubs. Conventional and hydrogen concepts realise the energy neutrality only barely. The fact that all elaborated concepts lead to energy neutrality in 2050 or earlier means that the transition based on the current energy infrastructure is possible. This way, the investments already made will not be lost.
- Based on the assumptions made here, energy neutrality of the built environment including personal transport is not feasible within a district. The energy consumption for personal transport will still be too high in 2050.

11. FOLLOW-UP STEPS

The research will be continued on various aspects of the above-mentioned energy concepts.

The Excel calculation model provides the degree of energy neutrality for 2020, 2035 and 2050. In 2050 and in some cases also in 2035, values higher than 100% occur. It is interesting to see which energy concepts or combination of concepts is for the involved municipalities the best to reach a certain degree of energy neutrality in certain year, for

example 20% energy neutrality in 2020, 50% in 2035 and 100% in 2045. This approach shows the difference between a feasible and desired degree of energy neutrality and thereby a freedom of choice, for example to carry out financial-economic optimisation of the concepts to be selected.

The energy hub concepts seem very promising. It would be interesting to elaborate various types of energy hubs.

An energy hub will be dynamically simulated in order to prove the added value of the exchange, conversion and storage of the energy flows within a district.

Next to the energy and CO₂ reduction, a further research can be done on exergy, clever utilisation of temperature levels of energy flows within an energy hub.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Economic Affairs of the Netherlands for their financial support of this research within the Energy Research Subsidy regulation (EOS) – long term –, and Mr Sander Koomen (Ymere housing association in Almere); Ms Marleen Bijker and Mr Theo van Es (municipality of Apeldoorn); Mr Fons Claessen and Mr Harm Eetgerink (municipality of Nijmegen) and Mr Pieter Biemans (municipality of Tilburg) for sharing information and their enthusiastic cooperation.

REFERENCES

- Apeldoorn barst van de energie (2009): (*Apeldoorn is bursting with Energy*)
- Koene, F. G. H.; Knoll B. (2008): "Renovation concepts for saving 75% on total domestic energy consumption", *Eurosun Conference, Lisbon, Portugal*.
- Masterplan Kanaalzone Noordoost, 2009
- Nederland krijgt nieuwe energie (*New energy for the Netherlands*) (2009): <http://www.nederlandkrijgtnieuwenergie.nl/main.asp>
- PEGO (2009); Stevige ambities, klare taal (*Strong ambitions, clear language*). Platform Energietransitie gebouwde omgeving (PEGO); Utrecht, the Netherlands.
- Roos, J.; Braber, K.; Willems, E.; Pfeiffer, E.; Kaandorp, A. (2009): Hybride LT-warmtenet (*Hybrid LT heating grid*); Waalsprong Nijmegen; report number: 80313, BuildDesk Benelux B.V.
- Visser, H.; Koene, F.G.H.; Paauw, J.; Opstelten, I.J.; Ruijg, G.J.; Smidt, R.P. de (2009): *Sustainable energy concepts for residential buildings, Packages of current and future techniques for an energy neutral built environment in 2050*, ECN-E--09-021. ("Building Future Potential study 2050"), ECN, Petten, the Netherlands

HOW MUCH ARE CONSUMERS WILLING TO PAY FOR IMPROVED AND GREENER ELECTRICITY SUPPLY? RESULTS FROM CHOICE EXPERIMENTS IN HYDERABAD, INDIA

Julian Sagebiel^{*1}, Kai Rommel² and Jens Rommel³

¹ *Humboldt University Berlin, Germany, Division for Cooperative Sciences*

² *Humboldt University Berlin, Germany Division of Resource Economics and International School of Management*

³ *Humboldt University Berlin, Germany, Division of Resource Economics*

ABSTRACT

The Indian State of Andhra Pradesh faces a significant power supply deficit of about five percent. By 2012 the installed capacity will increase by more than 8000MW but still be insufficient as the demand is estimated to grow by eight to ten percent. Over 50 percent of gross electricity generation comes from thermal (mainly coal) power plants and the share is still increasing which has adverse effects on climate and pollution. Additionally, transmission and distribution losses go up to 20%. These developments give rise to the need for alternative electricity supply solutions and more energy efficient consumption. While a lot of research is undertaken on the supply side, there is limited understanding on consumers' choices and preferences. This presentation will report on two consumer studies conducted in Hyderabad in March and Juli 2010. Both studies aim to elicit preferences for better electricity quality in terms of reduced power cuts and greener energy and use Discrete Choice methods to estimate demand functions and Willingness to Pay. The first study covered 800 private households from Hyderabad, Andhra Pradesh. Apart from questions on consumption, knowledge and attitudes, a choice experiment was included. Consumers were confronted with 9 choices with 2 generic alternatives each. Each alternative comprises different values (attribute levels) for attributes namely scheduled power cuts, unscheduled power cuts, share of renewable energy and organizational form of the distribution company. A cost attribute then allows estimating marginal Willingness To Pay for each attribute. The results indicate a strong preference for the reduction of power cuts but little understanding of renewable energy and climate change. The second, forthcoming study will focus on industrial consumers. The sample comprises 300 randomly selected low and high tension industrial consumers in Hyderabad. Industrial consumers pay the highest tariff for electricity and face long lasting power cuts, sometimes more than three days. Previous studies report high WTP for reduction of power cuts with revealed preferences methodology. This study however uses stated preferences and as above applies Choice Experiments which should give insights in preferences for timing and duration of power cuts as well as the perception of climate change and the willingness of industries to contribute to a greener energy mix. The results of both studies will also give insights to possibilities of collective action and decentralized electricity supply.

* Presenting Author: Julian Sagebiel (julian.sagebiel@staff.hu-berlin.de)

CZECH PUBLICS' ATTITUDE TOWARDS ENERGY ISSUES AND TOWARDS THE DESERTEC PROJECT

*Ivan Benes*¹ and Zuzana Benesova²*

¹ CITYPLAN, Czech Republic

² Cranfield University

ABSTRACT

Our society faces energy issues such as resource depletion, increasing demand, energy security and climate change. The DESERTEC project – “Clean solar power from deserts” - exploits the option to use a small area of the deserts in North Africa to provide all the electricity needs to Europe, Middle East and North Africa. As the Czech Republic is situated in Europe, it might be involved in this project. This paper presents research of the attitudes of the Czech public towards energy issues and towards the DESERTEC project. Results show that Czech people are aware of the issues related to energy security such as fossil fuel depletion and the threats linked to nuclear power. However the Czech public believes that nuclear power is a good solution to the energy crisis and is rather skeptical about renewable energy sources. Nevertheless, surprisingly, respondents have a very positive attitude towards the DESERTEC project. The most significant benefits are, according to respondents; ‘increase of independence from non- renewable energy sources’ followed by ‘environmental improvement’. With regard to potential benefits for the Czech Republic, ‘resource diversification’ is perceived as most important. The main barriers identified were bad relationships among the states of North Africa and Middle East, finance and lobbying by large energy corporations. The survey also revealed that the Czech public has a lack of information about the potentials of renewable energies. Thus while introducing the DESERTEC project the dissemination of information about renewable energy is essential, then emphasis should be placed on explanation of the technology of the project and on demonstrating examples where similar projects already exist, to avoid the skepticism about the projects’ feasibility.

Keywords: renewable energy, DESERTEC, Concentrating Solar Power, public attitude

* Presenting author: Ivan Benes (ivan.benes@cityplan.cz)

TENTATIVE IDEAS TO EXPLORE THE VIABILITY OF THE NUCLEAR OPTION

*François Diaz Maurin**

Unaffiliated

ABSTRACT

After the accidents at nuclear reactors of Three Mile Island (United States, 1979) and Chernobyl (Ukraine, 1986), the world has turned its back on the civilian nuclear industry. Since then, developing energy from nuclear sources had been widely abandoned, with a few exceptions, such as France. This has resulted in a *quasi*-moribund nuclear industry until the end of the 20th century. However, the early 21st century has created some circumstances that have changed the way countries regard the nuclear option when considering their mix of Primary Energy Sources.

Despite the turbulent times of the economic crisis, industrialized countries are looking for alternative energy sources in order to break the addiction to fossil energy, as well as to achieve energy independence. On the other hand, the global energy demand keeps rising, especially because of the economic growth of emerging countries. This is enough for the nuclear option to be seen as the energy source the most likely to overcome these challenges, so much so that some talk of a 'nuclear renaissance'. Indeed, nuclear energy proponents market it as an alternative energy, even sometimes calling it *sustainable*, able to produce 'CO₂-free', or 'zero-emission', energy that is available in large quantities, stable in terms of safety and security, and economically competitive.

However, I argue that the nuclear option is more a choice of circumstance rather than a result of a collective and social debate. Moreover, the new craze for nuclear energy seems to be based on old narratives about energy and sustainability. Consequently, it must be reconsidered whether or not nuclear energy is actually an alternative energy source. In other words, it must be verified whether or not this technology is viable. That being said, it shall be conceded that analyzing the feasibility of the nuclear technology is made difficult by the diversity of structures and functions involved in such a complex socio-economic system.

Nevertheless, recent discussions about energy and sustainability offer some tools to better frame energy analysis. In this paper, I will try to explore the possibilities of adopting the MuSIASEM scheme (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism), developed by Giampietro and Mayumi, as a framework to examine the feasibility and desirability of the nuclear option. As a starting point, I will try to identify the different concepts and variables to consider, especially the different parameters, scales, and criteria of performance. The reader will be also invited to provide critiques and advices based on these tentative ideas since particular attention must be paid to the definition of such a multi-scale integrated analysis. This is especially important since it intends to pave the way for a serious discussion about the future of the nuclear option as an alternative energy source.

Keywords: Nuclear Energy, Sustainability, Viability, Multi-Scale Integrated Analysis, MuSIASEM

1. INTRODUCTION

Nowadays, we certainly live a critical moment in which modern society depends more than ever on energy supply. At the same time the biosphere shows us that its resources are limited which is a fact that has been globally acknowledged only relatively recently. For that reason, the question of energy has become probably one of the most critical issues humankind will have to face during the 21st century. People in charge of finding solutions to this issue will be challenged as they will have to account for external

* E-mail: francois.diazmaurin@gmail.com – Cambridge, MA, USA

constraints (e.g. limits of the natural resources) as well as internal constraints (e.g. increase of population and energy consumption per capita). The existence of such constraints brings its share of questions whether it is actually possible to meet the future energy needs of humanity while being forced to accept the finiteness of the natural resources, or put in other words, the limited speed of the planet's capacity for regeneration.

Moreover, the current situation is not urgent only because of those constraints but also because our dependence to fossil energy has led to a human-driven climate change. This has become even worse due to the decrease of natural resource quality; so that we need more Primary Energy Sources to produce the same amount of Energy Carrier than in the past [Hall, 2008]. Therefore, the main challenge clearly is environmental and the question of energy is all about finding a path toward ecological sustainability when dealing with energy supply.

Given this challenging situation, some people have been looking for sources that are able to supply our needs for large amounts of energy, and so, for several decades. That is mainly the reason why nuclear energy has come back to the foreground of the debate about alternative energy sources to succeed to the fossil energy era.

2. STUDYING THE VIABILITY OF NUCLEAR ENERGY AS AN URGENT ISSUE

2.1. About the future of energy

As of today, there is no obvious solution to solve the question of energy, since every energy source has its pros and cons. As a result, the most viable alternative energy source may vary depending on which criteria of performance we give priority to. For instance, if we consider that the most important is to provide large amounts of energy, nuclear energy sounds to be a good candidate. On the contrary, if we want to minimize the danger related to the wastes coming from the energy production process, nuclear energy becomes right away less attractive. We will see later that (1) the criteria of performance need to come as a result of the public debate; and (2) the assessment of the viability of an alternative energy is more complex than a linear study as the previous sentence could have suggested.

As a matter of fact, studying our energy future is all about trade-offs between the different alternative energy sources so that the *solution* will certainly be a mix of those different energy sources. Having said that, the question now is whether every alternative energy sources should actually be part of the energy mix and, if so, with which balance.

2.2. Nuclear energy as a good candidate...

Given the current circumstances described above, nuclear energy is more and more seen as one of the energy sources most likely to solve the question of energy. Indeed, at first sight the simple equation is that the nuclear energy production process seems to be able to supply large amounts of energy using natural resources (uranium) that will be available at least through the 21st century [Deutch et al., 2003; Kazimi et al., 2010]. The new generation of nuclear power plant is also announced as being safer with a reduction of the probability of nuclear accident, while control measures can be taken in order to make the nuclear fuel cycle more secure in terms of proliferation [Deutch et al., 2003]. Now, if we add to this equation the fact that "nuclear power can potentially contribute significantly to reducing global warming" [Deutch et al., 2003], then we start to understand how much nuclear energy becomes a serious candidate, if not the most appealing one, in such a debate about alternative energy sources. Nuclear energy is finally often marketed by its proponents as an alternative energy able to produce 'carbon-free' energy that is available in large quantities, stable in terms of safety and security, and economically competitive.

2.3. ...but no consensus yet

At the same time, the possible deployment of the nuclear technology could be more difficult to achieve than expected given all the efforts that need to be made prior to its success. Indeed, some challenges have already been identified as required to be overcome if nuclear energy wants to play a role in the future of energy: the high up-front capital costs of the nuclear production processes, or the large amount of research efforts that remain to prove the regulatory feasibility of new designs as well as to find a long term management solution for high level wastes [Deutch et al., 2003] are only a few examples. And most of those challenges have remained until recently [Deutch et al., 2009]. In short, as Hall and Powers [2008] say, there are “great potential gains and great potential costs with nuclear power”.

Hall and Powers [2008] also remarkably pointed out that the ongoing opposition about nuclear energy is due to the fact that nuclear energy optimists rely on technology to overcome those challenges while nuclear pessimists mainly focus on uranium depletion to demonstrate that it would probably not be possible to overcome those challenges. This opposition demonstrates how strong the opinions about nuclear energy are, being positive or negative, which impact current studies about nuclear energy. As a result, Hall and Powers [2008] conclude that “only empirical analysis can assess the potential future of nuclear power”. However, we argue that performing an empirical analysis about nuclear energy actually means reaching a deadlock. Indeed, although empirical data are definitely necessary to any energy study, the problem with nuclear technology is that (1) empirical data can only be collected on a large number of plants in order to compare them, so once a given technology has already been developed and its deployment has already been engaged; and (2) those plants use different production processes from which data would not be directly comparable. As a result, studies about nuclear energy using empirical data are always performed once the necessary financial and human capitals have already been invested to the development and deployment of a new technology. Therefore, empirical studies can only assess the viability of current or past nuclear technological choices and cannot assess future production processes that are still under development which is contradictory with Giampietro et al.’ [2010] suggestion that “it would be wise to perform a *quality check* on the discussion of the future energy scenarios, by combining the old wisdom and the recent development in the field of energetics, before investing billions of € and US\$ on very dubious alternative energy sources”.

Lastly, there is no much doubt that there is still a large disagreement about the viability of nuclear energy, so much so that there is a risk of launching a new nuclear deployment before verifying its potential advantages. For that reason, assessing the viability of the nuclear option as part of the potential alternative energy sources is something that seems to be necessary and that has not been performed to date.

2.4. The problems encountered in current studies about nuclear energy

Existing energy studies about nuclear technology, even the most recent ones, present some analytical problems that right away put into question their conclusions and explain why there are so many discrepancies between their results. Those problems seems to differentiate themselves into two categories such as analytical problems (wrong assumptions) and conceptual problems (wrong methodology), with some studies cumulating both types of problems.

2.4.1. Analytical problems

Analytical problems occur when a given study mistakenly considers assumptions that are either not correct or not adapted to the study. This is illustrated by the disparity of the results found in studies that intend to have the same purpose, and apparently use the same methodology. For instance, studies assessing the life cycle carbon emissions of the nuclear energy production process published results from no less than 1.4 carbon dioxide

equivalent per kWh (gCO₂e/kWh) to 288 gCO₂e/kWh [Sovacool, 2008]. According to Sovacool [2008] who analyzed more than one hundred studies about the nuclear energy life cycle, these differences are due to the fact that lower bound studies miss some steps of the nuclear energy life cycle (e.g. plant construction, decommissioning fuel transportation, etc.), while upper bound studies consider unrealistic assumptions about the nuclear technology (e.g. nuclear power plant operation lifetime overestimated, outdated uranium enrichment process, etc.).

This type of problems is also at the origin of the discrepancy observed in studies evaluating the Energy Return On Investment (EROI) of nuclear energy, i.e. the ratio between the amount of energy delivered to the society (mainly electricity considered as the Energy Carrier) and the amount of energy put into the conversion process (considered as the Primary Energy Source) [Giampietro et al., 2010]. Indeed, published results go from an EROI less than 10:1 up to 60:1 [Hall and Powers, 2008], even 93:1 according to a study of the University of Melbourne [Sevior, 2010]. As Hall and Powers [2008] say and others already observed in previous studies, “this discrepancy on the EROI figure for nuclear has to be clarified as one of the most urgent energy issue”.

Those analytical problems seem to have two main origins related to the analyst or team of analysts who performed those studies: (1) lack of expertise about the nuclear energy production processes and different technologies; (2) lack of objectivity worsened by the existence of an *a priori* opinion that affects the integrity of the study and thus its results. Reibstein [2003] gives us a partial explanation to that problem as “critical experts on radiation injury, nuclear weapons proliferation, nuclear waste, operational accidents, nuclear materials, mining and refining, and alternative sources of energy do not have the money and institutional context of the nuclear proponents” which reduces the number of critical studies about nuclear energy. On the contrary, experts from the nuclear industry are certainly more likely to be nuclear optimists since it would be difficult for them to publish results that go against the nuclear energy deployment. As Upton Sinclair used to say “it is difficult to get a man to understand something when his job depends on not understanding it”. In short, they have an irrevocable conflict of interests which undermines the objectivity of their studies. On the other hand, opponents who have performed critical studies about nuclear energy are not always familiar with the nuclear industry so much so that they do not have the necessary expertise to avoid the analytical problems identified above. This justifies, if still necessary, the fact that a serious discussion, in terms of objectivity and expertise, must be engaged about the viability of nuclear energy.

2.4.2. Conceptual problems

Conceptual problems deal with the methodology used to perform an energy study, in terms of energy accounting for example. As of today, except studies that would have been missed here, it seems that there is no study that addresses this kind of problems. Indeed, most of the existing studies adopt a conventional linear view of the exploitation of Primary Energy Sources [Giampietro et al., 2010] which appears useful in some ways but certainly not sufficient to assess the quality of an energy source as described later in this paper. Indeed, a linear approach of energy accounting entails some reductionisms that affect the pertinence of the quantitative results. Such effects of considering a linear view in energy accounting are discussed in Giampietro et al. [2010].

Although some studies use a net energy approach to energy accounting which partially addresses the conceptual problems we just described (e.g. by performing an EROI evaluation), we found out that other conceptual problems remain. Indeed, existing studies about sustainability do not address the issues of scale, dimensions and/or time, and thus do not give a full picture of the nuclear energy production process since (1) they do not give meaning to their results in relation to different functions of the society (scales); (2) they assess only few criteria of performance (dimensions) without cross-referencing their results; and (3) they do not take into account qualitative changes over time.

A good way to illustrate those remaining conceptual problems is looking at how much not considering the qualitative changes over time can affect the results of a given

energy study. For instance, existing studies that intend to assess the availability of the natural uranium ore supply in the future often conclude that natural uranium will be available until the end of the century at reasonable price [Deutch et al., 2003; Kazimi et al., 2010], but never take into account the fact that the quality of the uranium ore (natural enrichment) will decrease over time, which will automatically increase the amount of 'energy for energy' used in the same production process. Put in other words, in that case the EROI is more-likely to decreased over time as technological improvements are much likely not to be able to offset this drop in the quality of natural resources.

As a matter of fact, it seems that there is a gap in the research about nuclear energy in terms of its viability and a serious discussion needs to be engaged. Now, the question is how to perform such an assessment of the viability of nuclear energy as an alternative energy source.

3. VIABILITY OF AN ENERGY SOURCE

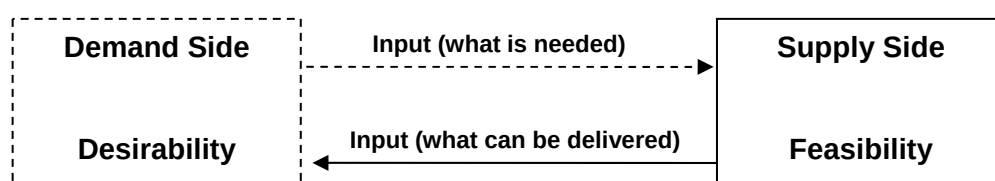
3.1. Feasibility vs. desirability

It is now time to formally define what we meant so far when speaking of the viability of an energy source. The viability of an energy source corresponds here to its quality. As explained by Giampietro et al. [2010], in order to discuss the quality of energy sources it is essential to be able to visualize and quantify the characteristics of the metabolic pattern in two independent ways providing a definition of the quality from the supply side (what can be delivered) and from the demand side (what is needed). In other words, assessing the quality of an energy source – or its viability – implies looking at its feasibility as well as its desirability. Indeed, the feasibility of a given technology represents the assessment from the supply side, while its desirability represents the assessment from the demand side.

Going further, the feasibility of a given technology can be assessed only after having decided a particular form of the metabolic pattern from the demand side, while the desirability can be assessed only after having decided a particular form of the metabolic pattern from the supply side [Giampietro et al., 2010]. Therefore, the discussion of the quality of an energy source is, in some ways, a chicken-egg problem in which assessing one side requires the other side already being assessed, and *vice versa*, as illustrated in Figure 1.

According to Giampietro et al. [2010], it is necessary to simultaneously look at the two sides when studying the energetic metabolic pattern of modern society, because assessing the quality of an energy source is all about matching the supply side with the demand side. According to the authors, this approach corresponds to a heuristic method intending to overcome the simplifications which imply reductionism and that are usually in use in standard quantitative analyses of energetic metabolic pattern of society. This is all the more important since discussing the quality of an energy source especially implies performing a quantitative analysis. As far as the chicken-egg problem cited above, we will discuss later in this paper how do deal with this issue by adopting the MuSIASEM analytical tool so that this issue can be turned in a way to test the robustness of the quality assessment of a given energy source.

Figure 1. The Chicken-Egg Problem of the Viability Assessment



3.2. Purpose of a viability assessment

As explained before, the quantitative assessment of the viability of nuclear energy is necessary since this technology intends to be an alternative energy source. Now, as Giampietro and Sorman [2009] rightly pointed out, “the pre-analytical definition of the purpose of the analysis will determine the usefulness and pertinence of the quantitative results”. In other words, it is important to provide a clear explanation of the purpose of such a discussion about the quality of a given energy source before actually performing the analysis. The general purpose of a viability assessment is to provide quantitative results of the feasibility and desirability of a given energy source as a support to the public debate about alternative energy sources. Indeed, the public debate consisting in comparing different possible energy scenarios cannot be done without the support from quantitative scientific studies. On the contrary, scientific studies cannot and should not fully assess the quality of an energy source without the participation of the society as a whole in selecting, even indirectly, the criteria of performance considered as being the most relevant. Indeed, a “scientific analysis cannot and should not be used to answer the question about sustainability (sustainability of what?; sustainability for whom?; sustainability for how long?). This is the role of humankind as a whole which has to decide how to deal with the semantics of sustainability” [Tainter, 2008; in Giampietro et al., 2008]. In general terms, it is not the role of scientific studies to answer questions from the demand side. Nevertheless, scientific studies can *help* answering those questions which should be the purpose of any analysis intending to assess the quality of an energy source.

4. TENTATIVE IDEAS TO ASSESS THE VIABILITY OF NUCLEAR ENERGY

We previously argued why having a serious discussion about nuclear energy is urgent, and what assessing the viability of an energy source actually is. Now, here are some tentative ideas, presented as successive steps, on how we could perform such an assessment of the potentiality of nuclear energy as an alternative energy source.

4.1. Step 1. Critical appraisal of the existing literature on EROI of nuclear energy, and generation of a new EROI analysis

A new EROI analysis about nuclear energy seems to be necessary given the discrepancy of existing results due to the analytical problems found in existing studies as we discussed before. As a preliminary step to this analysis, an exhaustive overview and critical appraisal of the existing literature on EROI of nuclear energy should be performed since it is not the purpose of this paper. Such appraisal should provide information especially about (i) what data are available; (ii) which protocols have been used; (iii) what types of problems can be found in the available data; as well as (iv) the main sources of uncertainty and ignorance.

The new EROI analysis will benefit from this critical appraisal avoiding as much as possible the analytical problems. This net energy analysis will especially have to take into account the correct and most significant production processes in relation to the different available nuclear technologies. Although empirical data will be limited or even not available, it would be wise to also analyze the EROI of future nuclear technologies that are still under development, such as breeder reactors, thorium powered nuclear reactors, potential fusion reactors and even increasingly popular small modular nuclear reactors. The EROI analysis will then have to make the right assumptions in terms of energetics for each production process using as much as possible empirical data making sure that they are suitable to the analysis and cross-referencing them with other available data.

This net energy analysis will be useful to give a technical explanation to different forms of the nuclear energy chain and to make it possible to represent the metabolic pattern of society in quantitative terms. Moreover, the EROI analysis will make it possible

to conduct a basic MuSIASEM analysis on the viability of nuclear energy as a Primary Energy Source.

4.2. Step 2. Development of an integrated assessment methodology of the performance of nuclear energy in relation to the metabolic pattern of modern society

After determining the potential supply of net energy and the relative requirement of inputs (on the biophysical side) it becomes possible to consider the non-equivalent costs and negative impacts of this net supply. In this second phase, the biophysical analysis of production of nuclear energy will be translated into an integrated assessment by considering different criteria of performance. This implies considering all relevant factors required to give meaning to the semantics. This can be obtained by explaining: (i) how the system functions from the inside; and (ii) its interface with the context. As a result of this analysis, it becomes possible to check the congruence between: (1) the assessment done according to the technical information gathered in the first step; and (2) the problem structuring of the public debate over nuclear energy in the society. Are we sure that the current public debate on nuclear energy is based on a right perception of its pros and cons? What are the criteria of performance the most relevant to the general public?

Such an integrated assessment of the performance of nuclear energy in relation to the metabolic pattern of modern society is made possible by using the Multi-Scale Integrated Assessment of Societal and Ecosystem Metabolism (MuSIASEM) scheme, developed by Giampietro and Mayumi [Giampietro et al., 2008], as a general framework. Indeed, the MuSIASEM could be an effective tool for this discussion thanks to its ability to represent criteria of performance of a socio-economic system in relation to different factors and different non-equivalent domains. The MuSIASEM is also a unique and advanced semantically open analytical tool that can link the system to the whole societal structure and give meaning to it.

In practical terms, here are some tentative ideas on how to adapt the MuSIASEM scheme to a viability assessment of nuclear energy. Readers willing to familiarize themselves with the rationale and theory involved with MuSIASEM will find an outline in Giampietro et al. [2008]. According to the definition of the authors, “the MuSIASEM scheme is an operationalization of Georgescu-Roegen's bioeconomic approach to the economic process that explicitly addresses biophysical feasibility and constraints” [Giampietro et al, 2008]. In other words, the MuSIASEM scheme is an analytical tool especially designed to study an economic process (such as the nuclear energy production process) in relation to its external constraints and its internal constraints. A system of (quantitative) accounting within the MuSIASEM scheme is defined using a set of different concepts explained as follows.

4.2.1. Parameters

Feasibility and desirability can be analyzed considering different parameters (or factors) depending on the metabolic pattern of the economic process in question, i.e. the exploitation of the Primary Energy Source. Each parameter (being economic, biophysical, social, etc.) is introduced as either a flow or a fund of the economic system into the flow-fund representation of MuSIASEM. As far as the feasibility and desirability assessment of the nuclear energy production process, we could identify the following parameters (but not limited to): (i) the Primary Energy Source (i.e. thermal nuclear energy); (ii) the Energy Carrier (i.e. electricity); (iii) the human time (working hours); (iv) the financial capital invested; (v) the quality of natural resources (natural enrichment of uranium ore); and (vi) the generated wastes (nuclear by-products, greenhouse gases, etc.).

The first two parameters come from the net energy analysis performed in step 1, while the other ones would have to be quantitatively evaluated at the time of the integrated assessment (step 3). Those factors need to be selected according to criteria of performance that are the most relevant to the general public, which will give the integrated

assessment its usefulness and pertinence. Therefore, the definition of such parameters is an essential step of a discussion about the potentiality of nuclear energy, and thus would require particular attention.

Once the key parameters (called extensive variables under the MuSIASEM scheme) are identified, they will be cross-referenced so that they can be expressed in terms of flow ratios, fund ratios or flow/fund ratios (called intensive variables). Those intensive variables will give an explanation of how the system functions from the inside. However, they will not be able to give information about its interface with the context which is essential to get a full picture of the economic system in relation to the rest of society.

4.2.2. Scales

In order to get a full understanding of the interface between the economic system and its context, it is necessary to look at the big picture of the technology in question, i.e. its role within the whole society, rather than focusing only on its direct economic pattern. This is made possible by considering different scales (or levels) when studying the viability of an energy source. The MuSIASEM scheme is especially a tool that allows to consider as many scales as necessary to perform the viability assessment. It links together factors from different hierarchical levels through a bottom-up analytical process from the level of the energy production process to the level of the society. In addition to make comparisons between the values of parameters referring to different hierarchical levels, the MuSIASEM approach can also be used to compare parameters being at the same hierarchical level but belonging to different places [Giampietro et al., 2008]. This will be useful when assessing the potentiality of nuclear energy or of its production processes, as discussed below, that can be located in different countries or regions.

In practical terms, some of the above cited factors can be evaluated at different hierarchical levels so that the flow-fund representation of the MuSIASEM scheme can be set at the interface between two successive levels. For example the human time factor can correspond either to the total time of human activity in the society (level n), the working hours of the paid work sector (level n-1), as well as the working hours of the energy and mining sector (level n-2). As far as the discussion about the viability of nuclear energy, it would be wise to perform the integrated assessment starting from level n-4 which corresponds to the level of the different production processes (mining; uranium enrichment; nuclear power plant operation; waste management; etc.) that take part of the nuclear energy sector (level n-3). This seems to be useful since (1) one production process can be used in different nuclear energy conversion technologies which viability can be assessed using mutual production process results; and (2) it becomes possible to identify which production process within a given technology is the weak link according to the criteria of performance we look at. In other words, performing an integrated assessment of nuclear energy down to level n-4 allows us to assess how the system functions inside in its deepest manner. In other words, it would not be realistic to assess the viability of the nuclear energy sector without looking at the level of its production processes.

4.2.3. Criteria of performance

As discussed above, the criteria of performance will have to be selected so that they are the most relevant to the general public since the purpose of the analysis is to support the public debate about alternative energy sources. Going further, this is especially the role of the society as a whole to decide which criteria are relevant and which ones are not. For this preliminary study, it is possible to identify some criteria of performance related to nuclear energy with no intention any of giving more importance to some criteria rather than to others. Such criteria of performance of the nuclear energy production economic system could be: (i) economical interest; (ii) amount of energy supplied; (iii) availability of the nuclear plants; (iv) safety of the nuclear operation; (v) non-proliferation of the nuclear fuel; (vi) radiation level of the nuclear wastes; (vii) nuclear fuel availability; (viii) environmental impacts; (ix) social impacts; etc. Note that there is no mention here about

how to express those criteria of performance in quantitative terms, and that one criterion of performance can be expressed using several quantitative variables.

After defining the parameters, scales, and criteria of performance of nuclear energy as discussed above we will come up with an analytical tool that is ready to use to actually perform the integrated assessment.

4.3. Step 3. Carrying out an integrated assessment of the potentiality of nuclear energy

Both the feasibility and the desirability of the nuclear option as an alternative energy source will be assessed using the findings gathered in the first two steps. While doing so, we will use two key conceptual tools that are related to the MuSIASEM scheme: (i) the mosaic effects, and (ii) the impredicative loop analysis [Giampietro et al., 2008].

Quoting the authors, “the combination of extensive variables and intensive variables gives us redundant but useful information to increase the robustness of the analysis”, which corresponds to the ‘mosaic effects across levels’. Later they add that “the generation of redundant information is also useful to see whether or not the data set coming from various sources are compatible with each other, or whether or not the assumptions about future scenarios are plausible”. This tool will be certainly of help to study the viability of nuclear energy given the discrepancy of results in existing studies and the need for cross-referencing empirical data as discussed above.

‘Impredicative’ is an adjective that qualifies a situation where “what is defined participates in its own definition” [Kleene, 1952; in Giampietro et al., 2008]. This corresponds to what we discussed before through the chicken-egg problem of any viability assessment. “Impredicativity is considered as a nuisance in scientific reductionism since it makes it impossible to establish a linear causation, which is a typical goal of traditional scientific activity” [Giampietro et al., 2008]. Usually, this problem is resolved in scientific analysis by choosing one particular linear causation which will be validated empirically. However, such an approach is not possible with a metabolic system operating on different levels [Giampietro et al., 2008]. As a matter of fact, “impredicative loop analysis is an attempt to deal with this problem within the MuSIASEM scheme” [Giampietro et al., 2008] by representing the reciprocal constraints between the different parameters and scales.

Finally, using these two key conceptual tools within MuSIASEM allows us to perform the integrated assessment discussed so far accounting for the non-linearity that exists with any sustainability analysis.

5. CONCLUSION AND RESULTS

5.1. Findings

The three main findings of this tentative exploration of the viability of the nuclear option as an alternative energy source are that (i) such a study is necessary; (ii) it has not been performed to date; and (iii) it is made possible using the MuSIASEM scheme described above.

In particular, we discussed the fact that the nuclear option intends to be a good candidate for the future of energy given the current economic and environmental circumstances. However, we pointed out the discrepancies between results of existing studies about nuclear energy which means that there is no consensus about its potentiality yet. Especially the discrepancies have been identified as coming from analytical problems and/or conceptual problems in existing studies.

Later, we defined the viability of an economic system as being both its biophysical feasibility and its desirability in relation to the metabolic pattern of modern society. Then it has been explained that the purpose of such a viability assessment is to support the public debate about alternative energy sources rather than answering alone the question

whether or not nuclear energy should play a role in the future of energy, since the final decision about the nuclear energy deployment remains the duty of the society as a whole.

Lastly, we tentatively explored how to engage a serious discussion about nuclear energy. Three steps have been identified in order to perform the viability assessment: (i) performing a critical appraisal of the existing net energy analyses about nuclear energy as well as performing our own EROI analysis; (ii) developing an integrated methodology of assessment adapted to nuclear energy; and (iii) carrying out the integrated assessment of the potentiality of nuclear energy using the findings gathered in the first two steps.

5.2. Conclusion

What is at stake with the future of energy clearly is whether or not human will be capable of co-evolving with the environment while meeting its energy *needs*. The term co-evolution [Kallis, 2007] means a process where we are able to change our identity if necessary rather than always trying to fix the outside world. This entails switching from a steady-state representation of the metabolic pattern of society to an evolutionary view [Giampietro et al., 2008] which latter view is at play here when intending to perform such an integrated assessment of the viability of nuclear energy. Moreover, assessing the quality of alternative energy sources is considered as being a pre-requisite toward co-evolution between modern society and the environment.

Finally, as we intended in this paper to pave the way for a serious discussion about the future of the nuclear option as an alternative energy source, the reader is warmly invited to provide critiques and advices based on these tentative ideas given that (1) particular attention must be paid to the definition of such an integrated assessment; and (2) this topic is considered as one of the most urgent energy issues.

REFERENCES

- Deutch, J. (Co-Chair); Moniz, E.J. (Co-Chair); Ansolabehere, S.; Driscoll, M.; Gray, P.E.; Holdren, J.P.; Joskow, P.L.; Lester, R.K.; Todreas, N.E. (2003). *The Future of Nuclear Power: An Interdisciplinary MIT Study*. Cambridge, Mass.: Report for Massachusetts Institute of Technology. URL: <http://web.mit.edu/nuclearpower/> (last connection on Sept. 18, 2010).
- Deutch, J.; Forsberg, C.W.; Kadak, A.C.; Kazimi, M.S.; Moniz, E.J.; Parsons, J.E.; Yangbo, D.; Pierpoint, L. (2009). *Update of the MIT 2003 Future of Nuclear Power: An Interdisciplinary MIT Study*. Cambridge, Mass.: Report for Massachusetts Institute of Technology. URL: <http://web.mit.edu/nuclearpower/> (last connection on Sept. 18, 2010).
- Giampietro, M.; Mayumi, K.; Ramos-Martin, J. (2008). "Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MUSIASSEM): An Outline of Rationale and Theory". *Working Papers from Department of Applied Economics at Universitat Autònoma de Barcelona (UAB)*. URL: <http://EconPapers.repec.org/RePEc:uab:wpdea:wpdea0801> (last connection on Sept. 18, 2010).
- Giampietro, M.; Sorman, A.H. (2009). *Interlinkages and Forecasting made possible by the use of the DECOIN analytical tool kit*. Deliverable 4.3 WP 4 – EU project DECOIN No. 044428 FP6-2005-SSP-5A. URL: <http://www.decoin.eu/deliverables/DECOIN%20D4.3%20Report%20of%20the%20Interlinkages%20and%20forecasting%20prototype%20tool.pdf> (last connection on Sept. 18, 2010).
- Giampietro, M.; Mayumi, K.; Sorman, A.H. (2010). "Assessing the quality of alternative energy sources: Energy Return On the Investment (EROI), the Metabolic Pattern of Societies and Energy Statistics". *Working Papers on Environmental Sciences, Institut de Ciència i Tecnologia Ambientals (ICTA), Universitat Autònoma de Barcelona (UAB)*. URL: <http://hdl.handle.net/2072/47934> (last connection on Sept. 18, 2010).
- Hall, C.A.S. (2008). "Why EROI matters". EROI on the web: (Part 1 of 6). *The Oil Drum*. April 1, 2008. URL: <http://www.theoil Drum.com/node/3786> (last connection on Sept. 18, 2010).
- Hall, C.A.S.; Powers, B. (2008). "The Energy Return of Nuclear Power". EROI on the web: (Part 4 of 6). *The Oil Drum*. April 22, 2008. URL: <http://www.theoil Drum.com/node/3877> (last connection on Sept. 18, 2010).

- Kallis, G. (2007). "When is it coevolution?" *Ecological Economics*, Volume 62 (1), 1-6. doi:10.1016/j.ecolecon.2006.12.016.
- Kazimi, M.S. (Co-Chair); Moniz, E.J. (Co-Chair); Forsberg, C.W.; Ansolabehere, S.; Deutch, J.; Driscoll, M.; Golay, M.W.; Kadak, A.C.; Parsons, J.E.; and Regalbuto, M.; (2010). *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study*. Cambridge, Mass.: Report for Massachusetts Institute of Technology. URL: <http://web.mit.edu/mitei/news/spotlights/nuclear-cycle.html> (last connection on Sept. 18, 2010).
- Reibstein, R. (2003). *Book Review: Double or Quits? The Global Future of Civil Nuclear Energy*: Malcolm C. Grimston and Peter Beck, Earthscan Publications Ltd., London, 2002, ISBN 1 85383 913 2 paperback, 237 pp. *Ecological Economics*, Vol. 47 (2-3), 217-218. doi:10.1016/j.ecolecon.2003.07.005.
- Sevior, M. (2010). *Everything you want to know about Nuclear Power: The Benefits of Nuclear Power*. University of Melbourne. URL: <http://nuclearinfo.net/Nuclearpower/TheBenefitsOfNuclearPower> (last connection on Sept. 18, 2010).
- Sovacool, B.K. (2008). "Valuing the greenhouse gas emissions from nuclear power: A critical survey". *Energy Policy*, Vol. 36 (8), 2950-2963. doi:10.1016/j.enpol.2008.04.017.

CAN AGRICULTURE PROVIDE US WITH BOTH FOOD AND FUEL?

Sheshti Johansson^{*1}, Karin Liljequist¹, Lars Ohlander², Kjell Aleklett¹

¹ *Uppsala University, Global Energy Systems, Department of Physics and Astronomy, Box 535, SE-751 21, Uppsala, Sweden*

² *Swedish University of Agricultural Sciences (SLU), Department of Crop Production Ecology, Box 7043, SE-750 07 Uppsala, Sweden*

ABSTRACT

The energy content of global agricultural production was calculated, and compared with the global food requirements. It was concluded that present edible production is enough for food, but not biofuel production as well. Theoretically, residues could give some biofuels. However, considering that present agricultural production is dependent on a high input of fossil fuels, the real energy exchange from converting residues into fuels may be very small. Therefore agriculture cannot replace any larger part of the fossil fuels used at present in the transport sector.

Keywords: biofuels, food security, agrofuels

1. INTRODUCTION

There is a large interest in biofuels, partly because of the depletion of oil reserves, but probably more because of a worry that green house gases emitted from combustion of fossil fuels will increase temperatures. At present there may be an overproduction of crops in many countries, but this is more or less because of the aid of fossil fuels. If the main condition for having a surplus of food is a cheap and secure supply of fossil fuels, is it wise to use such temporary surplus to replace fossil fuels in the transport sector? Is it possible for agriculture to produce biofuels to replace fossil fuels in the transport sector, while at the same time being dependent on fossil fuels for high yields? Can we do this, without adventuring food supply?

2. PREDICTING BIOFUEL POTENTIAL

There is no fundamental difference between growing crops for biofuel or growing them for food. Plants need water, good soil and nutrients, and these simple requirements limit the potential for expansion. Already there are problems with water access, loss of arable land due to erosion and salinization, competition with land use for roads and city expansion. On top of this, production of fertilizers is dependent on natural gas and finite mineral deposits. It is difficult to foresee the development on these different parameters, and thus predictions in future biofuel potential are very unreliable.

To avoid these difficulties we chose to investigate present food production. Instead of attempting any future prediction we investigated the theoretical limits to biofuel production from present production. This should give a reasonable estimate of what we can expect in the future. Or even more, what we can't expect in the future, taking into account that the production today is there because of a high input of fossil fuels.

^{*} Corresponding author: E-mail: kersti.johansson@fysast.uu.se; Tel. +46(0)735741416

3. BIOFUELS FROM AGRICULTURAL PRODUCTS

The calculations are described in detail in Johansson et. al (2010). Data on harvests were taken from FAOSTAT with reference year 2006, and multiplied with calorimetric energy contents for each crop. This resulted in a global gross production of approximately 20 000 TWh. After deductions for losses, such as storage losses and losses in upgrading, e.g. upgrading cereals into meat, the remaining part available for food was 7200-9300 TWh. Assuming each person needs 2500 kcal per day, and the global population is $6.7 \cdot 10^6$ persons, the food requirements are 7100 TWh. Thus no one today should have to starve. However, some of this production is used for other purposes, such as biofuels. In figure 1 some results are shown where it is assumed that the entire production of certain crops is used for biofuels. All scenarios in the figure have the consequence that food production will not be sufficient.

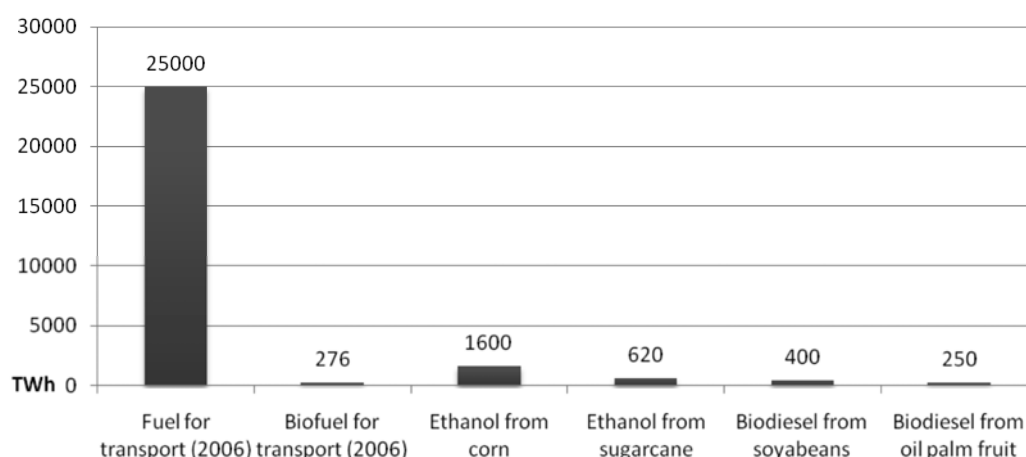


Figure 1. Amount of biofuel produced if total global production of some crops was used as feedstock, compared to the consumption of bio- and fossil fuels within the transport sector in 2006 (Johansson, et al., 2009).

The figure shows that very little fuel can be derived from the edible production, and certainly not without affecting food security. Therefore we also calculated the energy content in the residues produced from global agricultural production. The maximum theoretical limit turned out to be less than 8000 TWh (Johansson, et al., 2010).

4. DISCUSSION

The only chance for agriculture to produce biofuels without competing with food production is to use residues. However, these residues require energy to be harvested and upgraded to fuels, and the theoretical limit of less than 8000 TWh is not including any ratio of energy put into the system compared to the energy in the fuel. Some residues would not be available in a more closed agricultural system where nutrients are better recycled and crop and animal production integrated. Therefore it can be concluded that biofuels derived from agricultural products cannot even in theory replace the fossil fuels used in the transport sector.

ACKNOWLEDGEMENTS

Thank's to Professor Emeritus Sven Kullander, Royal Swedish Academy of Sciences, for taking initiative for this work.

REFERENCES

Johansson K., Liljequist K., Ohlander L., Aleklett K., 2010. "Agriculture as provider of both food and fuel". *Ambio*, 2010, volume 39 issue 2, pages 91-99.

HOW AND HOW MUCH CAN FOREST ECOSYSTEMS SUPPORT THE PROSPEROUS WAY DOWN?

Silvio Viglia^{*1}, Janis Gravitis², Salvatore Mellino¹, Enrique Ortega³, Alexandre Monteiro Souza³ and Sergio Ulgiati¹

¹ *Parthenope University of Naples, Italy*

² *Latvian State Institute of Wood Chemistry, Latvia*

³ *State University of Campinas, Brazil*

ABSTRACT

Can forest ecosystems play any important role in support of the sustainable living of populations day-by-day more addicted to fossil fuels, in times of declining nonrenewable resources? What is their carrying capacity concerning bioenergy and biomaterial supply as well as their ability to provide ecosystem services? Forests are claimed to be able to provide not only food, fibers, chemicals, construction materials, but also biomass as an alternative energy source as well as services of climate regulation, support to water cycle and uptake of emissions, not to talk of biodiversity protection.

Environmental protection is sometimes considered as competing with human presence and economic development. On the contrary, innovative concepts developed within the UNESCO's Man and the Biosphere Programme (MAB) recommend environmental protection to be achieved without banning human activities but instead developing appropriate management practices aimed at joint economic, social and environmental sustainability. The suitability of such practices must be assessed across spatial and time scales by means of appropriate evaluation methods that go beyond mono-dimensional measures and criteria.

The economic performance is the most commonly investigated aspect, also due to the strict although fragile relationship between extraction of natural resources and growth of economic activities. Instead, a comprehensive assessment should be implemented by means of a broader evaluation framework, taking into proper account different environmental aspects: mass, energy and energy flows, emissions, efficiency, integration of local activities, among other factors. In this study, we apply the SUsustainability Multimethod Multiscale Assessment (SUMMA) to investigate the interplay of forestry and nature conservation activities, in order to explore the resource use patterns and the existence of biophysical constraints to economic development, if any. The SUMMA approach allows the parallel implementation of both "upstream" (Material Flow Accounting, Embodied Energy Analysis, and Emergy Synthesis) and "downstream" (Exergy Analysis, Economic Analysis, as well as airborne, waterborne and solid waste generation and release) evaluation methods.

Our study deals with a selection of forest management practices and forestry activities in Europe in order to identify the resource investment needed for, and the benefits achieved from, joint environmental conservation and economic activity implementation, within the frame of a decreasing reliance on fossil fuels and the search for a prosperous way down ahead.

A special attention is placed on the evaluation of the standing natural capital, its use and turnover time, by means of the emergy method. Selected ecosystem services generated by the investigated systems are also evaluated in emergy terms to highlight their key role for the sustainable development of the local communities.

* Presenting author: Silvio Viglia (silvio.viglia@uniparthenope.it)

GROWTH MODELS: THE ROLE OF ENERGY

André Cabrera Serrenho^{*1,2}, Tânia Sousa^{1,2}, and Tiago Domingos^{1,2}

¹ Instituto Superior Técnico - Technical University of Lisbon, Portugal

² IN+ - Center for Innovation, Technology and Policy Research

ABSTRACT

Long-term economic growth predictions are not very reliable because there is a significant unexplained fraction of economic growth, known as the model's residual. Recent growth models have been developed that include biophysical constraints as production factors, such as energy services and natural resources. These models have reduced the unexplained fraction of economic growth, providing more reliable long-term predictions.

In this context, the literature has explored the possible causal relation between energy use and economic growth. It seems evident that historically the economic growth path is attached to an energy use growth path. Even though there are many doubts about the existence and the direction of a causal relation between energy use and economic growth, the inclusion of energy services as a factor of production produces a large reduction in model's residuals.

In this work we discuss the main theoretical assumptions of some recent models (Ayres 2008; Stern et al. 2004) that include energy as a factor of production and their accordance with the main stylized facts of economic growth in a broader and multidisciplinary perspective that encloses environmental / physical, economic and societal points of view.

We also perform an empirical validation of assessed models that include energy as a production factor by using recent data on primary energy consumption from 1995 to 2007 for the EU-15 countries, assembled in pooled cross-section datasets from Eurostat. We assess the magnitude of growth explained by energy. Furthermore, as we use disaggregated data for each source of energy, we evaluate their individual impact on output focusing on the differences between renewable and non-renewable energies. We also assess the indirect effects for each energy source, evaluating whether the economic value of energy is affected by its source, i.e. by its quality. This empirical validation will be performed using various energy measures, such as primary energy and useful energy.

REFERENCES

- Ayres, R.U. Sustainability economics: Where do we stand? *Ecological Economics*, 2008, 67: pp. 281- 310.
- EUROSTAT [online] *Statistics Database*. 2010. Available from Internet: <http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database>.
- Stern, D.I. and Cleveland, C.J. "Energy and economic growth". Rensselaer Polytechnic Institute, NY, USA, 2004, *Working Paper in Economics* no.0410.

* Presenting author: André Cabrera Serrenho (andre.cabrera.serrenho@ist.utl.pt)

MITIGATION POLICIES IN NON-ANNEX I COUNTRIES: IMPACTS ON COMPETITIVENESS OF BRAZILIAN ENERGY-INTENSIVE INDUSTRIES

Régis Rathmann , Alexandre Szklo and Roberto Schaeffer*

Energy Planning Program, Graduate School of Engineering, Federal University of Rio de Janeiro, Centro de Tecnologia, Bloco C, Sala 211, Ilha do Fundão, Rio de Janeiro, RJ 21941-972, Brazil

ABSTRACT

This study estimates the impacts on Brazilian industry of adopting a cap-and-trade mechanism starting in 2013. Findings revealed that the cement and mining segments would be the most affected in terms of increased relative prices and loss of market. The ferroalloys and mining segments would be at substantial risk of losing international competitiveness given their foreign trade exposure and the impact of the carbon cost on their prices. In the short run, free distribution of 80% of the permits would reduce the impacts on these vulnerable segments, but in the long run they would not be able to avoid losing international competitiveness. Therefore, this study examined the consequences of adopting low-carbon measures. Because of the long maturation period of investments in low-carbon processes, in the short run it would still be desirable to distribute free permits. Over the long term this allocation could be withdrawn. Thus, the best option to maintain the competitiveness of Brazilian industry would be a mixed strategy. In the short run, this would entail distribution of permits and incentives to implement low-carbon measures, while in the long run these permits would be withdrawn because the companies would have sufficiently absorbed this carbon cost and could maintain their global competitiveness.

Keywords: Brazil; cap-and-trade; industrial competitiveness; impacts

1. INTRODUCTION

The effect of any international climate treaty would be limited without the effective participation of the two countries with the highest greenhouse gas (GHG) emissions: China and the U.S. Together they are responsible for 42% of global emissions (IEA, 2009). Until recently skepticism prevailed over whether these countries would be willing to mitigate their emissions. However, both have recently changed their postures, in the U.S. with the progress of two congressional bills (H.R. 2454 and S.1733, in the House of Representatives and Senate, respectively) and with the Chinese declaration of voluntary commitments to reduce the country's carbon footprint, ratified at the 15th Conference of the Parties (COP 15) in Copenhagen in 2009. Like China, Brazil has also declared it will adopt voluntary measures to mitigate its GHG emissions (UNFCCC, 2010a and 2010b).

Despite the growing adoption of measures by countries to mitigate emissions, and the assumption that Brazil would benefit by reaching bilateral accords to carry out low-cost projects to reduce emissions, policies in response to climate change are asymmetric. On one side are the developed countries, with mandatory targets, and on the other the developing countries, with only voluntary targets. Brazil and China fall in the second category (Dalkmann & Binsted, 2010).

This imbalance has been attracting increasing debate in the literature over the possible economic impacts of these asymmetrical commitments, specifically in terms of the competitiveness of industrial sectors (Reinaud, 2005; McKinsey & Company, 2006;

* Corresponding author; E-mail: rathmann@ppe.ufrj.br; Phone: (+55-21) 2562-8760

Carbon Trust, 2008; Ho et al., 2008; Aldy & Pizer, 2009; James, 2009; McKibbin & Wilcoxon, 2009). These impacts would be particularly felt by more energy-intensive industries and those with relevant insertion in global trade (World Bank, 2007).

At first glance industry in Brazil has little relevance in terms of its contribution to total domestic GHG emissions². But its significant contribution to final energy consumption – approximately 38% of the total (MME, 2009), as well as to gross domestic product (GDP) – 27% of the total (IBGE, 2008), demonstrate that various industrial sectors would likely be affected by the implementation of emissions targets, thus negatively affecting the country's generation of wealth. Moreover, the significant insertion of some industrial sectors in foreign commerce³, irrespective of Brazil's position on adoption of mandatory emissions targets, could affect their competitiveness in global trade.

Therefore, this study attempts to ascertain the impacts on Brazilian industry of introducing a cap-and-trade system starting in 2013. As such, we measure both the impacts on production costs and on demand of Brazilian industrial sectors⁴ resulting from the adoption of such a system.

Finally, by analyzing the external vulnerability of each sector, we identify which sectors would be affected more in terms of international competitiveness. Besides this, we assess whether the adoption of low-carbon measures would soften those impacts, thus protecting Brazilian industry against loss of external competitiveness, and whether this implementation would be more effective than distributing free emissions permits to diminish the impacts of the carbon cost.

2. DEBATE ON THE IMPACTS OF CLIMATE POLICIES ON INDUSTRIAL COMPETITIVENESS AND FOREIGN TRADE

While there is the consensus over the effects of carbon costs on the price of energy inputs, there is a debate in the literature about the possible loss of competitiveness of sectors or individual companies subject to mandatory policies in relation to firms located in countries with lower or no mitigation costs (Reinaud, 2005; McKinsey & Company, 2006; Carbon Trust, 2008; Ho et al., 2008; McKibbin & Wilcoxon, 2009). Although there are differences regarding the size of the impacts, there is consensus on the transmission mechanism of the carbon cost effects.

Under the mechanism of free distribution of emissions permits, there are different levels of allocation. This generates surpluses and deficits of permits, creating a carbon market. In this market, companies (especially in energy-intensive sectors) that have short-term needs to acquire permits to meet their targets can do so from more energy-efficient firms with more permits than they need (Montgomery et al., 2009). This short-term need is generated by the fact that investments to mitigate emissions require long periods to mature. The purchase of permits and/or investments in mitigation measures entail costs, which are passed through to the final prices charged to downstream companies or end consumers. To a varying degree, depending on the availability of domestic and imported substitutes and aggregate income level, this will tend to increase demand for imported goods. This in turn will increase production of competing products from other countries, more so from countries with low or no mitigation costs. The upshot will be lower production in countries adopting more stringent climate policies and higher output in countries with laxer policies. In other words, the mitigation of GHG emissions in some countries can have the perverse effect of increasing emissions from other countries (carbon leakage). This effect will be stronger the higher the cost of carbon.

² Approximately 8.9% of total Brazilian GHG emissions in 2005 (MCT, 2009).

³ The ferroalloys, mining, iron and steel and pulp and paper sectors sell, respectively, 79%, 58%, 24% and 22% of their output abroad. On the other hand, the mining, chemicals, nonferrous metals and petroleum sectors acquire, respectively, 25%, 21%, 18% and 17% of their inputs from foreign suppliers (SECEX/MDIC, 2010).

⁴ We analyze the following industrial sectors: foods and beverages; ceramics (bricks and tiles); cement; iron and steel; mining and pelletizing; nonferrous metals; pulp and paper; chemicals; textiles; and others.

There is also consensus over the relation between competitive impacts on industry and the level of international trade insertion. The more involved an industry is in foreign trade, and the lower its transport cost vis-à-vis the aggregate value of its products, the greater will be the possibility of relocating productive activities and hence the carbon leakage, as well as the degree of lost competitiveness via substitution of domestic consumption by imported goods. This is especially true in countries whose main trading partners do not have emissions targets.

The divergence between authors mainly concerns the intensity of the impacts. On the one hand, some authors argue that the cost of carbon, particularly in countries with emissions targets, significantly burdens productive activity, leading: 1) in the short term to lost profits and higher prices, followed by increased imports, 2) in the medium term, to industrial relocation and carbon leakage, and 3) in the long term, depending on how strongly industry reacts, to a lesser impact of the carbon cost (Carbon Trust, 2008; Ho et al., 2008; McKibbin & Wilcoxon, 2009). On the other hand, other authors argue that these effects will not be significant, making protection measures like free distribution of emissions permits unjustified (Reinaud, 2005; Houser et al., 2008). The use of this mechanism, seeking to minimize the impact of the carbon cost, can even be considered a litigable subsidy under the rules of the World Trade Organization (WTO), for violating the principles of nondiscrimination contained in Articles I and III of the General Agreement on Trade and Tariffs – GATT (James, 2009).

Finally, there are authors who, although they agree with the transmission mechanism, deny its occurrence, since the main trading partners of countries with more restrictive climate policies tend also to have emissions targets. As a result of this, these countries have similar mitigation costs and thus equal competitiveness in multilateral trade (Aldy & Pizer, 2009; James, 2009).

3. IMPACTS OF CAP-AND-TRADE ON THE COMPETITIVENESS OF BRAZILIAN INDUSTRIAL SECTORS IN THE BASELINE SCENARIO

In this section we analyze the possible implications in terms of industrial competitiveness of adopting a cap-and-trade system in Brazil as of 2013. We consider the baseline scenario of energy consumption and carbon intensity of Brazil's industrial sectors obtained by Henriques Jr. et al. (2010). This involves measuring the effect of sectorial targets and levels of free allocation of emissions permits, in the short and long terms⁵, on the sectorial production costs, and consequently on the transmission of these costs to the final prices charged to consumers. In this case, we measure both the national and international effect (respectively in terms of lost domestic market derived from consumers' price sensitivity and the external vulnerability of each industry). We use the method formulated by McKinsey & Company (2006), whereby the variation in sectorial production costs (ΔC_i), given the carbon cost, is expressed by Equation 1:

$$\Delta C_i = \frac{CI_j \cdot P_c \cdot DP_j}{CP_j} \quad (1)$$

Where: " CI_j ", " DP_j " and " CP_j " represent, respectively, the carbon intensity (tonnes of CO_2 /tonne of final output), demand for emissions permits (given by the percentage difference between free permits and total permits in the sector) and production cost (US\$/tonne) of a given sector " j ", and " P_c " represents the carbon price (US\$/t CO_2).

We consider carbon prices in 2013 and 2020 of respectively US\$ 20.00 and US\$ 35.00 per t CO_2 . Alternatively, we consider a long-term scenario of US\$ 50.00 per t CO_2 . We also consider a short- and long-term scenario where sectors exposed to loss of

⁵ Our short-term horizon is 2013 and long-term horizon is 2020.

competitiveness, in function of their international insertion and the importance of the carbon cost on their productive activity, will receive free emissions allowances to allow them to remain competitive. In this case, the sectors analyzed and the allocation levels (80% in 2013 and 30% in 2020) are the same as those envisioned for incorporation in the EU ETS in its third phase, as of 2013.

The above calculation requires obtaining data from the literature on the cost of industrial production in dollars per tonne (metric ton) of output. To obtain this figure, we used the estimates of total sectorial production costs and total physical output contained in the databases of the Annual Industrial Survey and the Monthly Industrial Surveys for 2007, provided by IBGE (2010), converted into dollars at R\$ 1.80/US\$ exchange rate and updated to 2013 and 2020 using an average yearly inflation rate of 6.5%. In turn, to obtain the variation in production resulting from elasticity of consumer demand in response to the pass-through of the carbon cost to final prices, we considered the referential price elasticities of demand in the literature, respectively over the short and long term, in the scenarios with and without free allocation of emissions permits.

Finally, we consider that different industrial sectors will be affected differently by the carbon cost in terms of international competitiveness, depending on their exposure to global trade. To measure this exposure, based on the information on output and sectorial trade balances, trade exposure (t_i) is defined for each sector by Equation 2 (Weber & Peters, 2009).

$$t_i = \left(\frac{e_j}{x_j} \right) + \left(\frac{i_j}{x_j + i_j - e_j} \right) \quad (2)$$

Where: “ e_j ”, “ i_j ” and “ x_j ” represent exports, imports and domestic production of a given sector “ j ”, respectively.

3.1. Trade exposure and impact on sectorial prices resulting from the imposition of a cap-and-trade system in Brazil

From Equations 1 and 2 we measured the change in sectorial prices and variation in demand for 2013 in the reference scenario. We also obtained the trade exposure of the different industrial sectors analyzed for this same scenario (Table 1). At the start of a cap-and-trade program in Brazil, with an estimated carbon cost of US\$20/tCO₂, and without free allocation of emissions permits, the cement and mining sectors would be most affected in terms of increased relative costs. This reflects the significant share of energy costs in the total production costs of these sectors (about 26% for cement and 38% for mining), as well as the high carbon content of the main products of each sector. More than this, these sectors have a low production cost per tonne of the final product, meaning the carbon cost has a greater relative impact (Equation 1). These results corroborate the estimates of Green Design Institute (2008) for the U.S., where these same sectors would be most affected in function of a price of US\$ 30.00 per tCO₂ in 2013.

Measurement of the response of consumers in the short run if the added costs were passed through fully to final prices showed that the mining and ceramics sectors would experience the greatest revenue declines because of falling demand. While in the mining sector the decline would be attributed to the significant increase in prices, in the ceramics industry the erosion of demand would be due more to the existence of substitute products (e.g. marble and granite) (Ferraz, 2009).

Table 1. Trade exposure, change in prices (%) and variation in demand of industrial sectors as a function of a carbon price of US\$ 20/tCO₂ in 2013

Sectors	Trade Exposure Index	Carbon Intensity	Change in Sectorial Prices	Price Elasticity of Demand	Variation in Demand
			2013		
Foods and Beverages	0.17	0.16	0.64%	-0.18	-0.11%
Ceramics	0.17	0.23	4.41%	-0.99	-4.37%
Cement	0.02	0.65	10.21%	-0.28	-2.86%
Iron and Steel	0.53	1.45	4.15%	-0.14	-0.58%
Ferroalloys	1.01	0.59	3.75%	-0.23	-0.86%
Mining	1.02	0.57	14.10%	-0.30	-4.23%
Nonferrous Metals	0.31	0.70	1.53%	-0.15	-0.23%
Pulp and Paper	0.43	0.51	3.91%	-0.29	-1.13%
Chemicals	0.66	0.47	1.71%	-0.39	-0.67%
Textiles	0.28	0.11	0.14%	-0.74	-0.10%
Other Industries	0.17	0.37	0.56%	-1.04	-0.58%

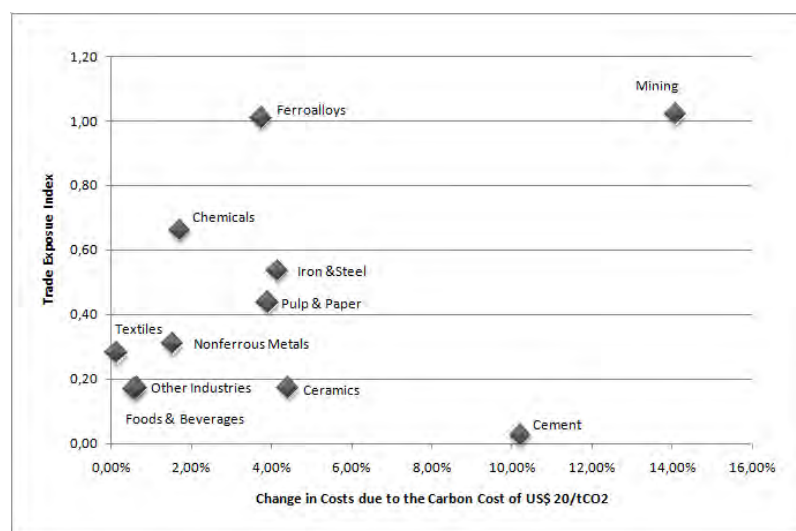


Figure 1. Change of costs and trade exposure of Brazilian industrial sectors in 2013 under a cap-and-trade system

Finally, adding the trade exposure index to the short-term analysis suggests that the cement sector would not be affected in terms of international competitiveness. Indeed, the low aggregate value of cement through its productive chain makes international cement commerce uneconomic (Carbon Trust, 2008). On the other hand, the mining and ferroalloys sectors, although less affected by the carbon cost, would be more affected by lost competitiveness because of their high exposure to foreign trade (Figure 1). In these sectors, the high aggregate value of the products and higher supply than domestic demand (Reinaud, 2005; James, 2009) lead to significant exports, particularly of iron ore and steel alloys. This means Brazilian companies would be more subject to lost competitiveness against rivals in countries with lower or no carbon cost.

Over the long run, the sectors most affected in terms of a change in costs due to the carbon cost would be mining and cement (Table 2). As in the short term, the mining and ceramics sectors would be those most affected by lost demand, though for different reasons. Demand for minerals is inelastic, because the products of the mining sector have captive demand, such as from the civil construction sector (Henriques Jr. et al., 2010). The fall in demand can be attributed to the incremental affect of the carbon cost on prices, unlike the variation in demand for ceramics, where a price increase because of the carbon

cost would lead to a fall in demand proportional to the increase in relative prices, because of the existence of substitute products. In turn, the textile sector would be less affected, both from an increase in prices and a loss of market (fall in demand).

Table 2. Change in prices (%) and variation in demand (output) of industrial sectors as a function of carbon prices of US\$ 35 and 50/tCO₂ in 2020

Sectors	Change in Sector Prices (%)		Price Elasticity of Demand 2020	Variation in Demand (%)	
	US\$35/tCO ₂	US\$50/tCO ₂		US\$35/tCO ₂	US\$50/tCO ₂
Foods and Beverages	1.12%	1.60%	-0.47	-0.52%	-0.75%
Ceramics	7.72%	11.03%	-1.55	-11.97%	-17.10%
Cement	17.87%	25.53%	-0.35	-6.25%	-8.93%
Iron and Steel	7.26%	10.37%	-0.25	-1.82%	-2.59%
Ferroalloys	6.56%	9.37%	-0.49	-3.21%	-4.59%
Mining	24.67%	35.24%	-0.38	-9.37%	-13.39%
Nonferrous Metals	2.68%	3.83%	-0.19	-0.51%	-0.73%
Pulp and Paper	6.84%	9.77%	-0.55	-3.76%	-5.38%
Chemicals	2.99%	4.27%	-0.48	-1.44%	-2.05%
Textiles	0.24%	0.34%	-0.97	-0.23%	-0.33%
Other Industries	0.98%	1.39%	-1.37	-1.34%	-1.91%

Based on the above analysis, the sectors potentially most exposed to lost competitiveness in Brazil would be mining, ferroalloys, iron and steel, pulp and paper, chemicals and cement. It is thus particularly necessary to measure the impact of distributing free permits to these sectors, aiming to keep them internationally competitive. In this case, like what is envisioned for the third phase of the EU ETS, we estimated whether the softening effect on the carbon cost of allocating 80% of emissions permits at no charge in 2013, and 30% in 2020 (EC, 2008).

It can be seen in Figure 2 that 80% free allocation of emissions permits in 2013 would significantly soften the impact of the carbon cost from implementing a cap-and-trade mechanism in Brazil. In relation to the scenario without free allocation, there would be a smaller decline in demand. Therefore, it would be an effective policy over this horizon to maintain the domestic competitiveness of the industrial sectors most affected by a restricted emissions scenario.

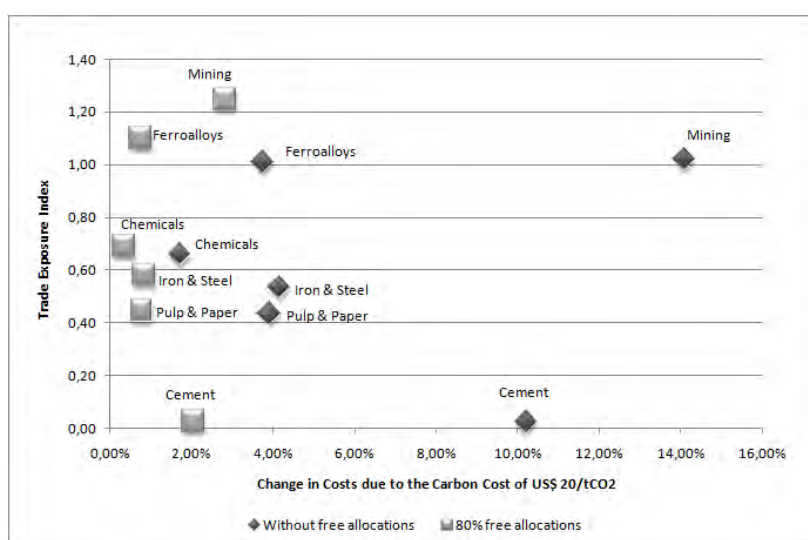


Figure 2. Change in costs and trade exposure for Brazilian industrial sectors exposed to loss of competitiveness in 2013, with 80% free allocations

However, this smaller decline of domestic demand would mean a proportional reduction in imports, and the smaller cost increase because of the free permit allocation would lead to a partial recovery of international competitiveness. This would be reflected in an increase in exports. In this case, the increase in exports resulting from lesser pressure on costs because of the free allocation would be proportionally greater than the fall in imports. Thus, the sectors analyzed would have greater trade exposure than under the scenario without allocation of free emissions permits. Nevertheless, since the increase in costs would be significantly smaller than in the scenario without allocation, and since competitiveness is a function of two factors (costs and trade exposure), the sectors would be significantly less exposed to a loss of competitiveness. This recovery of competitiveness would be restricted to the short run (Table 3). In the long-term scenario, where there would be less free allocation of emissions permits, the mining and cement sectors in particular would once again have a significant increase in costs. This would erode their competitiveness, inducing relocation of productive activities to countries with looser climate policies. This phenomenon would have the direct effect of deteriorating the trade balance of these sectors in Brazil and would also have indirect impacts on the economy and environment: a fall in the level of sectorial employment and output, along with carbon leakage.

Table 3. Change in prices and variation in demand of the industrial sectors exposed to international trade with 30% allocation of free emissions permits in 2020

Sectors	Change in Sector Prices (%)		Variation in Demand (%)	
	US\$35/tCO ₂	US\$50/tCO ₂	US\$35/tCO ₂	US\$50/tCO ₂
Cement	12.51%	17.87%	-4.38%	-6.25%
Iron and Steel	5.08%	7.26%	-1.27%	-1.82%
Ferroalloys	4.59%	6.56%	-2.25%	-3.21%
Mining	17.27%	24.67%	-6.56%	-9.37%
Pulp and Paper	4.79%	6.84%	-2.63%	-3.76%
Chemicals	2.09%	2.99%	-1.00%	-1.44%

Hence, the level of free permit allocation envisioned for 2013 would substantially reduce the impact of the cap-and-trade system, both on the production cost and the external vulnerability of Brazilian industrial sectors. The long-term analysis reveals that decreasing the level of free allocations would increase the external vulnerability of the sectors analyzed, raising questions about the efficacy of this system in protecting industrial competitiveness. Indeed, a climate policy aiming to mitigate emissions at minimum cost, thus generating smaller competitive impacts in the domestic and external markets, should encourage the various sectors to adapt to new market conditions. This raises the question of whether the adoption of low-carbon measures in Brazilian industry would be more effective than distribution of free emissions permits to minimize the carbon cost impact from imposing a cap-and-trade system in Brazil starting in 2013.

4. COMPETITIVE IMPACTS OF LOW-CARBON MEASURES ON BRAZILIAN INDUSTRY UNDER THE CAP-AND-TRADE REGIME

In this section we investigate whether the adoption of low-carbon measures to reduce the energy consumption of Brazilian industry starting in 2010 would be more effective, under a cap-and-trade system, than granting free emissions permits. For this purpose, we use as a reference the low-carbon scenario of Henriques Jr. et al. (2010), which is a variation of the baseline scenario used in this study, considering the introduction of technologies with lower carbon intensity.

4.1. Impacts of the competitiveness of Brazilian industrial sectors in a low-carbon scenario

To measure the effects of a low-carbon scenario on the external competitiveness of Brazil's industrial sectors, it is first necessary to obtain new carbon-intensity estimates. For example, lower energy consumption to produce steel over the 2013-2020 period could reduce the carbon index from its current level of 1.45 (tonnes of CO₂/tonne of final output) to 1.32 in 2013 and 0.98 in 2020. This reduction in the sector's carbon footprint could be achieved because of the great potential to implement energy efficiency measures, in particular the adoption of new processes. Among these are: a) deactivation of obsolete low-capacity and inefficient blast furnaces, b) introduction of dry quenching and advanced wet quenching, and c) installation of top pressure recovery turbines, among others (Henriques Jr. et al., 2010).

The implementation of low-carbon measures to reduce energy consumption, besides lowering carbon intensities, would alter sectorial production costs because of the need to make new investments. While the introduction of new processes between 2013 and 2020 would reduce the carbon content, it would also increase relative production costs. For example, in the iron and steel sector the cost of making steel would rise from US\$ 698.88/tonne to US\$ 976.12/tonne, while in the mining sector the cost of producing iron ore would increase from US\$ 80.87/tonne to US\$ 85.77/tonne.

Based on applying the new estimates for the low-carbon scenario in Equation 1, considering a carbon price of US\$ 20.00/tCO₂, with no free allocation of permits, the cement and iron/steel sectors (just as in the baseline scenario) would be the most affected by a cap-and-trade system in terms of higher production costs in 2013. However, the impact of adopting low-carbon measures starting in 2010 would also lead in 2013 to a small reduction in the sectorial production cost increases in relation to the scenario without free allocations (Table 4). In terms of variation in demand, this smaller increase in final prices to consumers would reduce the impact in terms of smaller domestic consumption in relation to the scenario without free allocations.

Table 4. Change in prices (%) and variation in demand of the industrial sectors in the short term according to the scenario (baseline and low-carbon)

Sectors	Change in Sector Prices			Variation in Demand		
	Without Allocation	80% Allocation	Low Carbon	Without Allocation	80% Allocation	Low Carbon
Cement	10.21%	2.04%	8.97%	-2.86%	-0.57%	-2.51%
Iron and Steel	4.15%	0.83%	2.70%	-0.58%	-0.12%	-0.38%
Ferroalloys	3.75%	0.75%	2.75%	-0.86%	-0.17%	-0.63%
Mining	14.10%	2.82%	12.59%	-4.23%	-0.85%	-3.78%
Pulp and Paper	3.91%	0.78%	3.57%	-1.13%	-0.23%	-1.04%
Chemicals	1.71%	0.34%	1.55%	-0.67%	-0.13%	-0.60%

Since measures to reduce energy consumption require long periods for the investments to mature, in the short run the 80% allocation of free permits would be a more effective measure to maintain overall industrial competitiveness (Figure 3).

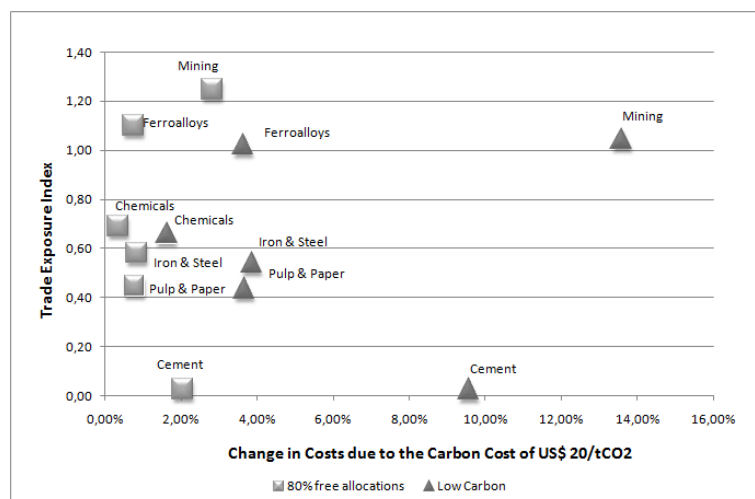


Figure 3. Change in costs and trade exposure of industrial sectors exposed to lost competitiveness in 2013 under the low-carbon scenario with carbon price of US\$ 20/tCO₂ and 80% allocation of free permits

However, considering only the sectors exposed to lost competitiveness – mining, ferroalloys, iron and steel, chemicals and pulp and paper – the adoption of low-carbon measures would be preferable to handing out free permits to maintain international competitiveness in the long run (Figure 4). In the case of a carbon price of US\$ 50.00/tCO₂, the adoption of low-carbon measures, by the mining sector, for example, would reduce the trade exposure and impact on costs significantly less than would 30% distribution of free emissions permits.

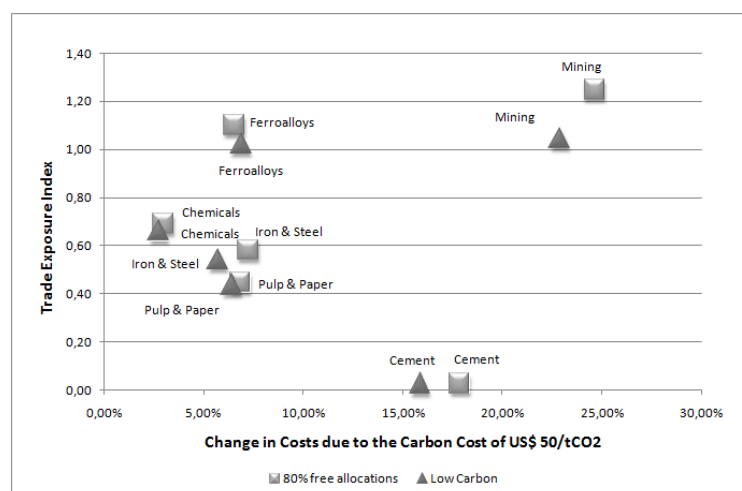


Figure 4. Change in costs and trade exposure of industrial sectors exposed to lost competitiveness in 2020 under the low-carbon scenario with a carbon price of US\$ 50/tCO₂ and 30% allocation of free permits

Therefore, in the short term there should be extensive free allocation of permits to protect the competitiveness of the industrial sectors that are most vulnerable to international trade. However, over the long term, the adoption of low-carbon measures would be preferable than a regime of reduced distribution of free permits.

5. CONCLUSIONS

Based on the assumption that Brazil will adopt a cap-and-trade system starting in 2013, we initially analyzed the economic and commercial impacts of the emissions targets under this system in a baseline scenario of emissions and energy consumption. The cement and mining sectors, both in the short and long run, would be the most affected in terms of an increase in their relative prices and loss of market. In turn, the mining and ferroalloys sectors would be most exposed to lost competitiveness. Finally, the lowest impact/exposure would be felt by the nonferrous metals and ceramics sectors, due to the low impact of the carbon price on their total production costs and their low insertion in international trade.

Therefore, the relevant impacts on some Brazilian industrial sectors would be a barrier to the implementation of a mandatory GHG emissions target regime in Brazil, such as a cap-and-trade system. A measure to soften the effects of lost competitiveness would be allocation of different levels of free emissions permits. In the short term, 80% distribution of free permits would reduce the negative impacts on the sectors most exposed to global trade, but in the long run these sectors would resume losing competitiveness in the global market. Besides, WTO rules would pose a possible barrier to the adoption of free permits (James, 2009). This distribution could be construed as an indirect subsidy to Brazilian industry, which could lead, for example, to countervailing measures against exports from the sectors receiving the permits. Because of this, there are questions about the effectiveness of such a policy.

Thus, we formulated a low-carbon scenario, considering the potential measures that can be implemented by Brazilian industries to reduce their carbon intensity. Since investments to achieve these reductions take substantial time to mature, in the short run, just after implementing a cap-and-trade system, it would still be desirable to distribute free permits to maintain the competitiveness of the sectors most vulnerable to the international market. However, in the long term, this allocation could be (and so as not to constitute a barrier, should be) phased out, because the low-carbon measures would already be in effect, causing the impact of the carbon cost to be less in this system than with free distribution of permits.

Therefore the best option to maintain the competitiveness of the Brazilian industrial sectors that are vulnerable to foreign trade would be a mixed strategy, including both allocation of free permits and adoption of low-carbon measures in the short term. Then, as the low-carbon measures mature, the free permit allocation could be phased out.

ACKNOWLEDGEMENTS

We thank CAPES, CNPq, and FBDS for their financial and institutional support for this study. We are also grateful to anonymous reviewers for their comments on the original version of the study.

REFERENCES

- Aldy, J. E., Pizer, W.A. 2009. "The Competitiveness Impacts of Climate Change Mitigation Policies". Pew Center on Global Climate Change, pp. 1-41.
- Carbon Trust. 2008. *EU ETS impacts on profitability and trade: A sector by sector analysis*. Available at <http://www.climate-estrategies.org>. 40p.
- Dalkmann, H., Binsted, A. 2010. *Copenhagen Accord NAMA Submissions: Implications for the Transport Sector. Bridging the Gap, Pathways for transport in the post 2012 process*. February 2010. 8p.
- European Commission - EC. 2008. *Amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community*. Available at <http://register.consilium.europa.eu/pdf/en/08/st03/st03737.en08.pdf>

- Ferraz, G. T. 2009. *Cement e Ceramics para Revestimento: Documento Setorial. Projeto PIB: Perspectivas do Investimento no Brasil*. UFRJ/UNICAMP, 62 p.
- Green Design Institute. 2008. *Economic Input-Output Life Cycle Assessment (EIO-LCA) model*. Retrieved June 2008.
- Henriques Jr, M. F., Dantas, F., Schaeffer, R. 2010. "Potential for reduction of CO₂ emissions and a low-carbon scenario for the Brazilian industrial sector". *Energy Policy* 38, April 2010, pp. 1946-1961.
- Ho, M. S., Morgenstern, R., Shih, J. 2008 "The Impact of Carbon Price Policies on U.S. Industry". September 26, 2008. Working paper.
- Houser, T., Bradley, R., Childs, B., Werksman, J., Heilmayr, R. 2008. *Leveling the Carbon Playing Field: International Competition and U.S. Climate Policy Design*. Washington, DC: The Peterson Institute. 117p.
- Instituto Brasileiro de Geografia e Estatística - IBGE. 2008. "Matriz de Insumo-Produto Brasil: 2000/2005". *Contas nacionais*, n. 23. Rio de Janeiro: 2008. 57p.
- _____. 2010. *Pesquisa Industrial Anual Empresa*. Available at <http://www.ibge.gov.br>.
- International Energy Agency - IEA. 2009. *CO₂ Emissions from Fuel Combustion. Highlights, 2009 Edition*. 124 p.
- James, S. 2009. *A Harsh Climate for Trade: How climate change proposals threaten global commerce*. Cato Institute, Center for Trade Policies Studies. Washington, D.C., 20p.
- McKibbin, W. J., Wilcoxon, P. J. 2009. "The Economic and Environmental Effects of Border Tax Adjustments for Climate Policy". *Working Paper in International Economics*, February 2009, n. 1.09. Lowy Institute for International Policy. 25p.
- McKinsey & Company and Ecofys. 2006. *EU ETS Review: Report on International Competitiveness*.
- Ministério de Ciência e Tecnologia - MCT. 2009. *Inventário brasileiro das emissões e remoções antrópicas de gases de efeito estufa – informações gerais e valores preliminares*. Ministério da Ciência e Tecnologia, Nov./2009, 19 p.
- Ministério de Minas e Energia – MME. 2008. *Balanço Energético Nacional 2007. Resultados Preliminares, Ano Base 2008*. Rio de Janeiro: EPE, 2009.
- Montgomery, D., Baron, R., Bernstein, P., Bloomberg, S., Ditzel, K., Lane, L., Smith, A., Tuladhar, S., Yuan, M. 2009. *Impact on the economy of the American Clean Energy and Security Act of 2009 (H.R. 2454)*. CRA International.
- Reinaud, J. 2005. *Industrial Competitiveness under the European Union Emissions Trading Scheme*. International Energy Agency, 92p.
- Secretaria de Comércio Exterior – SECEX/MDIC. 2010. *Sistema ALICE. Balança Comercial Brasileira. Janeiro a Dezembro de 2008*. Available at <http://www.mdic.com.br>. Retrieved on July 13, 2010.
- United Nations Framework Convention on Climate Change - UNFCCC. 2010a. *Draft Decision - /CP.15. Copenhagen Accord*. Available at <http://unfccc.int/resource/docs/2009/cop15/eng/l07.pdf>. Retrieved on March 1, 2010.
- _____. 2010b. *Annex I Parties: Quantified economy-wide emissions targets for 2020*. Available at <http://unfccc.int/home/items/5264.php>. Retrieved on March 1, 2010.
- Weber, C. L., Peters, P. P. 2009. "Climate change and international trade: Policy considerations in the US". *Energy Policy* 37, pp. 432-440.
- World Bank, 2007. *International Trade and Climate Change*. World Bank, Washington, D.C.

BUILDING UP A PROSPEROUS WAY DOWN IN BRAZIL

Ortega, E.*¹, Ferraz, J. M. G.², Comar, M.V.³, Odum, E.C.⁴

¹ LEIA, DEA/FEA, Unicamp, Campinas, SP, Brazil

² PPGADR, São Carlos Federal University, Araras, SP, Brazil

³ FCBA, Grande Dourados Federal University, Dourados, MS, Brazil

⁴ Professor Emerita, Santa Fe College, Gainesville, Florida 32606, USA.

ABSTRACT

The world's situation demands a systems diagnosis to identify what is wrong with the interaction of economy and nature to steer us in the search for solutions. The book "A Prosperous Way Down" of H.T. and E.C. Odum was written with this purpose, it can help us deal with the transition to a new stage of Human Civilization based on renewable production and consumption patterns. Nevertheless, the experience in Brazil with the application of the ideas in this book made us realize that their recommendations are adequate for Northern Hemisphere countries, where people have access to land, money stocks, political representation, education, but not in the Southern Hemisphere where people suffer strong oppression from dominant classes, through ideological frameworks provided by laws, media, schools, universities and religious systems. During transition, scientific communities from the North should join efforts with Social Movements of the South that have similar future perspectives, but may differ in theoretical and philosophical perspectives. It is necessary to identify some points of convergence in order to work together in a synergic way: (1) We should move to a low (fossil fuel) energy system, but at the same time, to a high renewable energy system; (2) We need to substitute the main beliefs of a destructive neo-classical economy by ecological systems principles strongly concerned with social issues. Even the capitalist system has a great inertial moment, at the same time, the Earth's biophysical system is reaching, or even over-riding, its resilience limits, such that no more growth is possible; (3) The anthropocentric approach should be overcome, because environmental services depend on the existence of habitats for other species; every species and every human-being is as important as the other one, no matter where they live and what they do; (4) The capitalist culture should be fully understood in order to be substituted by other cultures able to effect Earth's recovery; (5) In the South there is no a consensus about Population Decrease as well as in the North there is not a consensus about Consumption Reduction. Probably, both are economic competition forces. No nation will agree to reduce both if the other countries do not do the same. The solution of this impasse involves social assets redistribution, adoption of ecological forms of production and consumption and relocation, therefore a massive and revolutionary global transformation; (6) It is important to participate, in a convenient form, of important global actions as the Climate Change Movement, proposed by the Indigenous People Meeting in Bolivia, as well as the Global Degrowth Movement discussed in Europe.

Keywords: Prosperous Way Down, resilience, Biosphere, Climate Change, Global movements

Introduction

The ideas expressed in the book "A Prosperous Way Down" are very important and could be very useful in the transition we are living, but it is difficult their application (in any country). Here we discuss these difficulties and also how to overcome them. Presently in Brazil the more attuned discussions and concerns to these ideas are the national programs that finance industries and research institutions to study and apply means to

* Ortega, E.: ortega@fea.unicamp.br
Ferraz, J. M. G.: ferraz@cnpma.embrapa.br
Comar, M.V.: vitocomar@ufgd.edu.br
Odum, E.C.: bodum@cox.net

reduce CO₂ emission, and the payment for environmental services to rural properties owners. Most people ignore Odum ideas, including those that think and write about future scenarios in different public and private organizations. We think that the same thing is happening in other countries. Why? Probably because the people that agree with Odum ideas do not use Internet resources in a pro-active form and in an adequate language for most of the population. Even some futurologists who know Odum do not use his ideas and privilege other points of view, probably they consider that Odum ideas are not viable in an global economy that is driven by capitalist forces. Other motives could be: difficulties to understand the concepts of life cycle analysis and total aggregated energy, or emergy, and lack of courage to incorporate the values of negative externalities in economic accounting that demand a socially critical perspective.

Brazilian Parties positions compared with Odum proposals

Table 1. Identification of Odum main ideas

The main ideas for the future contained in the book “A Prosperous Way Down” (Odum e Odum, 2001).

General Vision 1	Social and environmental reforms to establish a transition from Capitalism to a Social System based on Sustainable Communities. Regional programs for an ecological ruralization (Gunther, 2004)
Agriculture 2	Integrated agricultural and agro-ecological systems, with recycling to maximum renewable carrying capacity. Rural production surplus allows developing small size towns. Rural systems will incorporate people that emigrate from cities and rural areas affected by lack of fuel, population growth, pollution and Climate Change. Incorporation of negative externalities and of areas of environmental services and absorption of environmental impacts.
Industry and Commerce 3	Proposals for new short-cycle transformation chains with equitative distribution of overall benefits.
Environment 4	Recovering of ecosystems, recuperation of native forest species in agricultural systems. Mitigation of and adaptation to the effects of Climate Change.
Education 5	Education is complemented by the perspective of System Ecology and Political Ecology.

Table 2. Broad vision of Brazilian political parties (Odum points of view, % of vote intention)

PSOL: Socialism and Freedom Party (Odum ideas: 1, 2, 3, 4)	PV: Green Party (2, 4)	PT/PMDB: Workers Party / Brazilian Democratic Movement Party (only 4)	PSDB/DEM: Brazilian Social-Democrats / Democrats (none)

Important Social Reforms within Capitalism (1%)	Qualified Growth within Capitalism (11%)	Competitive Growth within Capitalism (54%)	Subordinated Growth within Capitalism (27%)
Emphasis on Agrarian Reform and Human Rights. Promotes peoples mobilization for a decisive role in the country's management. The vision is of a Democratic Socialism, akin to ecologic causes which it considers complementary. There is no explicit long term perspective, which affects policies for the differing sectors of the economy and for nature. The proposal for education is to improve the present system with greater overall public access.	Support to national entrepreneurs in the various sectors of the Economy. It presents a vision of Green Capitalism, without a position in relation to the Agrarian Reform. Implementing procedures for socio-environmental certification of the different production chains and units. Searches for a special treatment of the Amazon Region.	Neoliberal politics with a certain precautions. A consortium of entrepreneur groups with good relations with Government, Trade Unions and some social movements. Negative growth factors are not considered within a proposal for development. Economic policy favors a vision of competition with other countries for the global market. Partial opening towards international capital for the production of biofuels. Lack of knowledge and criteria to define what would be sustainable	Practices strictly neoliberal politics, with no limitations, with a strong connection to the great international capital. It doesn't consider negative growth factors. Favors a vision of alliance with the countries which dominate the global market. Total opening to international capital to produce biofuels and mineral extraction. There is no interest to study the issues behind Sustainable Development and doesn't consider the issues of Climate Change.

Only two parties (PSOL and PV) show coherence with the Prosperous Way Down ideas but both have small chances to obtain the power (12% of votes). PT/PMDB and PSDB/DEM have 53 and 27% of votes.

Table 3a. Analysis of Political Parties Programs in relation with climate change and resilience loss:
(A) Direct correlation; (B) Indirect correlation; (C) Negative correlation.

PSOL Socialist and Freedom Party	• Re-discussion of the Decennial Energy Plan, aiming to adequate it to the requirements for the reduction of Green House Gases emissions; • Anticipation of deadlines and increase in the goals of CO₂ equivalents emission reduction in the National Plan for Climate Change; • Incentives for fast public and non-polluting transport, moved by renewable fuels and support to the creation of bicycle networks in Brazilian cities; • Incentives for public transport vehicles rather than individual automobiles; • Tax increase on manufacturing and Sales of polluting vehicles and/or consumers of fossil fuels; • Maintenance and betterment of the Brazilian Forestry Code; • Ecological Agrarian Reform to combat desertification and mitigate the effects of the draught in the semi-arid region.
B	• Changes in the present Forestry Law, substituting it by one that might guarantee the concession of forests for sustainable management practices, by cooperatives and riverine, extractivist populations, rural communities of black slaves descendants (<i>Quilombolas</i>) and small farmers without concessions for

	large national and multinational capital; • Re-nationalization of the electricity sector, with financing to end transmission distribution and energy consumption losses; • End of subsidies to the great energy consumers, amplifying the scope of the social energy tax; • Universalize the access to water, which must be recognized as a fundamental right of every human being and should be offered by the State, thus reverting privatizations in this sector, with the public management of water and the guarantee of its social control; • Use of the social taxation for water and energy use, increasing tariffs for the large consumer industries; • Recuperate and amplify the national and urban railway networks, linking it in large cities with metros and pre-metro systems. • Incentives for an intermodal transport system which fosters the rational use of waterways.

Table 3b. Analysis of Political Parties.

PV Green Party A	• Development of alternative energy sources: use of solar energy and stimulus to technology transfer to reduce costs and enhance performance; • Incentives for research and application in wind, geothermic and tidal energy sources.
B	• Proposes a policy for a sustainable energy matrix based on the economy, on the end of tax privileges and on the adoption of clean, efficient and non-polluting technologies; • Better use of natural gas, in transportation, construction of natural gas plants, with a price reduction for transport and energy generation; • An aggressive implementation of a national economic program for the energy sector, involving distribution networks, equipment, industrial products and home utilities; • Construction of small size hydroelectric plants such as mini-dams and subaquatic turbines; • Halting construction of new nuclear power plants, including Angra dos Reis.

Table 3c. Analysis of Political Parties Programs in relation with climate change and resilience loss:
(A) Direct correlation; (B) Indirect correlation; (C) Negative correlation.

PT Workers Party A	• Strengthening of international initiatives to implement a new global agreement to further actions for tackling the process of Climate Change; • Adjusting the Brazilian energy matrix with the increase of production and use of clean and renewable energy sources.

B	• Consolidating the paradigm change for the promotion of sustainable development of the Amazon and its furtherance for the remaining Brazilian biomes; • Intensification of integrated policies for the combat against deforestation; • Promotion of policies for the reduction of energy consumption, with technological innovation and combat against unnecessary waste; • Strengthening of Brazilian environmental legislation; but supporting the flexibilization of the Forestry Code; • Widening of the scope of specific programmes for the protection and sustainable use of Brazilian biodiversity; • Perfecting the integrated management of national water resources; (polemic projects such as the transposition of the São Francisco River and the construction of great dams); • Priority of planning actions is for the promotion of integrated urban and environmental policies.
C	• Stimulus to the creation of industrial centers in the areas of biotechnology (favorable to the liberation of transgenic seeds) and agribusiness.

Table 3d. Analysis of Political Parties Programs.

PSDB/DEM Brazilian Social Democratic Party/Democrats A	• Support to Brazilian participation in international agreements to reduce global warming risks and to deal with their consequences. • Focus on implementing zero deforestation rates – the drastic reduction of the cut-and-burn of forests – applying the strength of all existing legislation against offenders.
B	• Considers that deforestation must be contained as much as forest burning; • Save from destruction the precious Amazonian and Atlantic Forest (Mata Atlantica) biodiversity is an issue of both national and global interest.
C	• For its coalition with the DEM, a large part of its declarations are questionable, as DEM fosters as its basic principle the maintenance of agribusiness as the main economic centerpiece. Defining “agribusiness” as the sum of three decisive factors: production + technology + commercialization; • Favorable use of transgenic crops; • Works to elaborate a flexible Forestry Code, reducing present requirements; • It is against agrarian reform and, therefore, to land redistribution, a fact which would help the decrease in land concentration and the process of re-ruralization; • It makes no reference to the change in the energy matrix; • There is also no mention to a plan of water management.

The vision of large enterprises concerned with sustainability

Large corporations also present their proposal for Sustainable Development: the “Vision for 2050 Project”, developed by the World Business Council for Sustainable Development - WBCSD. This organization integrates 29 large enterprises concerned with the future within their growth-centered vision and proposes a timetable of changes,

starting now until 2050. Their project establishes a pathway which will require changes in governments' structures, in economic guidelines, in business, enterprise and citizen behavior. The proposal states that these changes are both necessary and viable; offering great business opportunities incorporating sustainability in their practices. The project aims to find answers for three questions: How would a sustainable world be like? How could we achieve it? What role can the entrepreneurial sector play to advance more rapidly towards this goal? The proposals for the sector for 2050 listed in the WBCSD document include:

- **An entrepreneurial leadership:** to become a defending agent for actions of sustainable development.
- **Policy Development:** to help develop new policies creating benchmarks for entrepreneurial contribution to sustainable development.
- **Practical Studies:** develop and promote entrepreneurial cases for sustainable development.
- **Better Practices:** to demonstrate entrepreneurial contribution to sustainable development and share better practices between members.
- **Global Reach:** contribute for a sustainable future for developing regions and regions in transition.

In short, WBCSD proposes a model which articulates complex alliances for socioeconomic development involving the private sector, NGOs, related to paradigms that structure and establish new and complex alliances. It proposes a consumer awareness rising for the acquisition of low-impact products, establishing a connection between consumers and enterprises. Information and communication technologies will play a significant role within this environment, allowing consumer access to product information, reevaluate their opinions, sharing amongst themselves and with the firms that develop and sell their products. It therefore reinforces the strategy of continued growth, with greater responsibility. It also uses an example from the World Bank, where a country with a solid development, which achieved 10 more mobile phones for each 100 people, would further its GDP by 0.8%. Thus still promoting the idea of economic growth!

Climate Change or Climate Disaster

According to KlimaForum (2010) the rapid world climate changes, with increasing calamities, could lead to the elimination of various human communities and of biodiversity thus proposing the reflection that calling them climate changes is practically to manipulate a reality, as we are in fact living a climatic disaster.

Anthony Giddens, apud Leite (2010) one of today's most influential sociologists and the main ideologist of the Third Way, searching for an alternative between radical liberalism and traditional social-democrat-state tendencies, turns his attention to the theme of global warming already admitting the need of a strong action by the State and of greater regulatory measures, of a longer range planning than in the past, to more effective market control mechanisms than in the last 30 years. He evaluates that "we are in the initial stages to discover what might be a new model of capitalism which is responsible and global" and foresees a convergence in the debate on the great recession and on the challenges of climatic change. Giddens also defends the idea that rich countries have to bear 95% of the costs in the fight against global warming within the next years, as "it isn't morally correct nor would it be practically feasible to impede the developing countries to develop".

We thus have to clarify the difference between growth and development, to be able to advance in the discussions towards urgent decisions. The development of a society depends on the way in which it profits from the benefits of its economic performance, which is a subsystem of natural resources, to distribute opportunity of access to common

goods: civic liberties, health, education, decent jobs. According to Veiga (2010), therefore, prosperity will also have to consider the environmental sustainability of this process. Thus the belief derived from economic growth which has been fostered for decades, Sunkel and Gliglio (1980) apud Veiga 2010 had as its premises:

- a) Faith in unlimited exponential economic growth;
- b) The possibility to sustain on the long term a style of development based on export of natural resources;
- c) Conduct geared to accumulate the maximum of natural goods for consumption;
- d) The advantages of urban concentration;
- e) Indiscriminate faith on scientific and technological progress and its unrestricted capacity of artificially reproducing nature;
- f) The possibility of compatibility between the high consumption levels of industrialized countries and of high-income groups of undeveloped countries and that of obtaining similar consumption levels for the great majorities.

A human dilemma

The human specie should develop an internationally coordinated program very rapidly, clearly conceived, fair and flexible, to reduce the population in the next centuries (CAIRNS, 2003). This effort will likely require a global population shrinkage of at least two-thirds to three-fourths, from a probable, mid-to-late 21st century peak in the 9 to 10 billion range to a future (23rd century and beyond) "population optimum" of no more than 2 to 3 billion.

Resources and Population Changes (number of people, renewables consumption and life style)

Good quality of life for everyone is the goal when considering population, whether in the North or South. As fossil fuels are used up and become more expensive, everyone will learn to live with less. Knowing how much we must cut down can help us plan ahead.

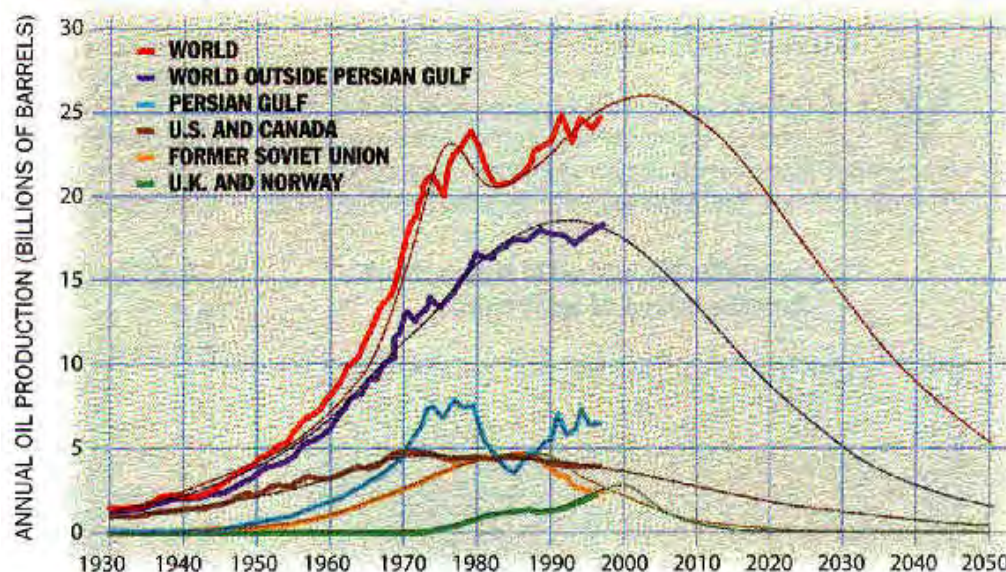


Figure 1. Graph from a Gas and Oil Industry report shows world oil production peaking in about 2004. Oil is the major nonrenewable source of energy (Campbell, 1998).

We are beyond the peak of fuel production.

Disasters like the oil spill in the Gulf of Mexico and Iraq war are examples which show that oil extraction and drilling deeper in the earth and farther out at sea, uses more energy than it produces.

One way to measure of quality of life is resource use per person.

To measure resources and their use is by emergy¹ calculations. The ordinary measure of standard of living is money per person, but money does not include the whole economy. The money flows (Gross National Product) do not include factors as sun, wind and rain. Emergy is a measure of total resources including money, and also sun, rain, and wind.

Emergy per person is a more inclusive measure of the “standard of living” in a country.

Emergy use can be divided into renewables and nonrenewables. Renewables have constant flows, such as sun, rain, wind, geological uplift, tide, and deep heat. Non-renewables include materials that are being used up, such as oil, coal, natural gas, uranium, and other minerals. The realistic measure of standard of living includes the calculation of the use of all these.

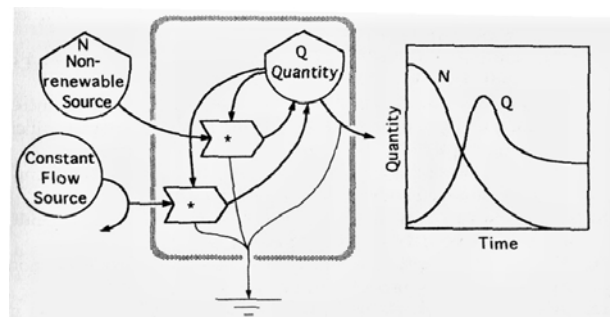


Figure 2. Civilization (Q) uses a constant renewable flow (R) (sun, rain, wind) and non-renewable fossil fuels (N). When N is used up, Q survives using only renewable resources (R).

As the economy uses up nonrenewables, it will depend more on renewables. By calculating the total emergy use of a country now, and then **what the emergy use will be when the nonrenewables are gone**, we can envision the changes: (a) if a country's population remains the same as emergy use decreases, the emergy per person will become less; (b) **If the population decreases at the same rate as the emergy use decreases, the emergy per person can remain the same.** The following table shows how much emergy will be available as nonrenewable fuels and minerals are used up. We calculate future standard of living by renewable emergy per person. Table 4 gives values for several countries. **Emergy per person** now is the total emergy use of the country divided by the population. When the country is living on renewable emergies only, the emergy per person is the **renewable emergy divided by the population**. To calculate how much the population must decrease to maintain the same emergy per person, the percent renewable emergies are of the total emergy is calculated. That percent reveals the population that can be sustained on renewables only.

Table 4. Calculation of sustainable population using Sahel Project database (2007).

Country	Population	Total emergy use seJ/y	Renewable emergy use seJ/y	% on renewable	Renewable emergy use seJ/y/person	Sustainable population
Argentina	39.786.850	2,91E+24	2,31E+24	79%	5,81E+16	31.583.376
Brazil	192.924.506	7,07E+24	3,53E+24	50%	1,83E+16	96.325.814
Venezuela	26.814.843	1,03E+24	3,93E+23	38%	1,47E+16	10.231.294
USA	308.758.000	1,88E+25	2,27E+24	12%	7,35E+15	37.280.886
Portugal	10.669.883	9,44E+23	3,92E+22	4%	3,67E+15	443.071
Italy	60.231.214	4,14E+24	6,75E+22	2%	1,12E+15	982.031

Using this table, we see that:

- Countries that are now more rural and less industrialized will have to make fewer changes.
- Since Argentina uses 79% of renewables, it will only need to decrease its population by 21%.
- Brazil will need to reduce its population 50% to maintain its present standard of living based on renewables consumption (not total consumption).
- Venezuela is an intermediate case, without fossil fuels should decrease its population to less than half the present value.
- However, the United States will have to reduce its population or its emergy per person by 86%. Many in the United States realize their emergy use per person is excessive. They are trying to cut down wasteful use.
- The worst cases are those of Portugal and Italy that should decrease their population in great number or their level of living could diminish enormously.

Reduction of the use of non-renewables

There are many proposals for reducing our dependence on nonrenewables. A recent indigenous convention wrote this:

“We call on States not to promote commercial monoculture practices, nor to introduce or promote genetically-modified and exotic crops, because according to our people's wisdom, these species aggravate the degradation of jungles, forests and soils, contributing to the increase in global warming. Likewise, megaprojects under the search for alternative energy sources that affect Indigenous Peoples' lands, territories, and natural habitats should not be implemented, including nuclear, bio-engineering, hydroelectric, wind-power and others. “(World Peoples' Conference on Climate Change and the Rights of Mother Earth)

Most proposals for the transition combine some reduction in wasteful use of resources and some reduction in population.

Ideas suggested by E.C. Odum (2010) that could be successful in all the countries, in the North as well as in the Southern Hemisphere.

1. Decrease urban concentration;

2. Increase rural villages with families living on the land;
3. Build sturdy basic housing;
4. Increase low-intensity (ecological) agriculture around the villages; use fewer machines and share what you have; less fertilizer and pesticides; more human labor - can come from the unemployed in the cities;
5. Encourage communities with diversity of nationalities, with each keeping special cultural values;
6. Organize enough government to give every person a basic safety net of food, housing, education, and medical care;
7. Reduce dependence on cars – communication can replace transportation;
8. Encourage smaller industries using less fuels;
9. Decrease unearned income, stocks, loans, bonds;
10. Cut down on luxuries and waste;
11. Educate for a diversity of jobs, with internships;
12. Encourage women to become educated, own property, establish businesses, make reproductive choices - in many countries, this has resulted in fewer children and stronger families.

The Degrowth Conference in Barcelona in 2010 put out this statement concerning population. “Denouncement of top-down population control measures and support of women’s reproductive rights, conscious procreation and the right to free migration while welcoming a decrease in world birth rates; (Degrowth Declaration Barcelona, 2010)

13. Maintain stable families and values - fewer children, decreased resources, and fewer cars;
14. Do not produce anything that cannot be recycled or reused;
15. Develop trade equity, based on emergy calculations;
16. Share information world-wide;
17. Maintain natural environment – this will be hard with increasing pressures on water, soil, fish, and forest resources

An introduction to the question of global governance:

Who would lead these changes? Not the corporations with the vision to sustain growth and maintain the capitalism even with more responsibility if the governments are held hostage by them?

A paradigm change is essential for life to continue (Comar, 2005). A civilization based on the three interrelated components of ideology, organization and technology is not sufficiently guided in its rightful development, unless the concept of transcendence pervades the ideological component. Governments have to change their perspectives towards planetary partnership and renewable resource use; scientists must cease to connive with materially oriented market forces; economists stop viewing competition as the only value, and environmental processes just from a consumer-based perspective; education needs to quest for fundamentals, for social inclusion, for virtues. Commercial exchange and international relations will have to use emergy values for agreements. Planning organizations will have to acquire this new perspective using transparent participative processes. Teaching and research institutions will have to offer solutions for priority issues, whose very nature will force them to structure multidisciplinary teaching

and research methodologies, socializing results and redirecting efforts towards mass communication and demystification of scientific knowledge. Our cities or conurbations must give place to more modest settlements, sustainably inserted within their ecosystems. Their internal functional and spatial organization must allow us to rediscover urbanity, the sense of belonging, of cultural identity, within a humane scale. This requires a political will and a continued and profound public consultation process with adequate channels and tools. Resources drain from poor to rich countries cannot be subsidized by scientists. New integrated systems, within a new scale, must be sought within the agro-ecological movement, respecting the need and wisdom of natural cycles, producing for local and regional needs, according to ecosystem characteristics and within more cooperative forms of management. World unity and global governance must be considered as the pivotal conceptual benchmark of a newly acquired human consciousness. Not a type of unity which would force all to a monotonous cultural conformity, but a spiritual thrust engendered on the belief of the intrinsic nobility of the human spirit. Something which will awaken the most subtle melodies of the kaleidoscope of human experience and creativity which the various and subsequent civilizations have entrusted us. A new moment in mankind's development, where superior values and attributes, surprisingly still alive in the human spirit, will gradually give form, revealing mankind's full potential, overcoming the rebel, bigoted and covetous posture of a deranged past adolescence. Where human beings rival to achieve unprecedented heights of service, not just for knowledge by itself, but for an ideal of perfection that could take us to our destiny: peace and community.

Nowadays, there is also the important idea of transformation of The World Social Forum into the Fifth International (Amin, 2005, 2008; League for the Fifth International, 2010).

Conclusions

It is difficult to change any country by means of the political system as it structured at present moment, but the analysis made can help us to identify political parties and institutions that are more close to Odum ideas that could be open for dialogue, or at least to establish individual contacts.

It is necessary to publish Odum books in other languages. An effort in this sense is now in course in Brazil.

It is necessary to create an international network about Prosperous Way Down book ideas using internet resources (for example: Wikipedia) in many languages with sites in all the countries, all of them with freedom to discuss local issues but also able to integrate efforts as a unique network.

REFERENCES

- Amin, S. 2005. *Samir Amin ideas*. Site: <http://www.fifthinternational.org/content/samir-amin>
- Amin, S. 2008. An *interview with Samir Amin*. Site: <http://www.ludd.net/retort/msg00980.html>
- Cairns, J. "A capacidade de carga, o crescimento exponencial e as guerras por recursos". Volume 14, Number 1, Fall 2003.
- Campbell, C. J., & Laherrere, J.H., 1998. "The end of cheap oil". *Scientific American*, v. 278, no. 3, p. 78-83.
- Comar, M.V. "Universal values for social innovations – a new ethical vision". *Review: Biologi Italiani*. Anno XXXV – n. 5, May 2005. Rome, Italy.
- KlimaForum 10. *Political Platform*. Site: <http://red-ecomunidades.blogspot.com/2010/08/political-platform-of-klimaforum10.html> (acesso em 09/09/2010)
- Gunther, F. "Ruralisation a way to alleviate Vulnerability Problems". In Ortega, E. & Ulgiati, S. (editors): *Proceedings of IV Biennial International Workshop "Advances In Energy Studies"*. Unicamp, Campinas, SP, Brazil. June 16-19, 2004. Pages 37-64. Site: <http://www.unicamp.br/fea/ortega/energy/Folke.pdf>
- League for the 5th International, 2010. Site: http://en.wikipedia.org/wiki/League_for_the_Fifth_International

- Leite, P. D. Anthony Giddens fala sobre "A Política de Mudança Climática". Site: <http://www1.folha.uol.com.br/ilustrissima/793679-anthony-giddens-fala-sobre-a-politica-de-mudanca-climatica.shtml> (acesso em 06/09/2010)
- Odum, E.C. Personal contribution to orient this manuscript writing. 2010.
- Sahel Project: Environmental Accounting and Systems Synthesis of Land Management Interventions at Multiple Scales in the Sahel Region of West Africa, 2007. *Emergy indices of World Countries with year 2000 database*. Site: http://sahel.ees.ufl.edu/database_resources.php
- Second international Conference on Economic Degrowth for Ecological Sustainability and Social Equity. 26-29 March 2010, Barcelona* Site: www.degrowth.eu
- Smail, J. K. "Redução da população mundial: Confrontando o Inevitável". *World Watch Institute*, Setembro /outubro de 2004, V.17 n.5 disponível em: <http://www.worldwatch.org/node/563> (acesso em 08/09/2010).
- Veiga, J.E. "Indicadores de sustentabilidade". *Estudos Avançados*. Vol.23 no. 68, São Paulo, 2010. Site: http://www.scielo.br/scielo.php?pid=S0103-40142010000100006&script=sci_arttext&lng=pt
- World Business Council for Sustainable Development (WBCSD) *Vision 2050. The new agenda for business*. 73 pages printed material, 2010.
- World Peoples' Conference on Climate Change and the Rights of Mother Earth. Site: BOLIVIA: *Indigenous Peoples' Declaration* (April 25, 2010). Site: <http://bsnorrell.blogspot.com/2010/04/bolivia-indigenous-peoples-declaration.html>

METHODOLOGIES: THEORY AND APPLICATIONS

Recalde M. and Ramos-Martín J.

ON WHY ARGENTINA IS INCREASING ITS ENERGY INTENSITY: A MULTI-SCALE INTEGRATED ANALYSIS OF ITS ENERGY METABOLISM

Ariza-Montobbio P. and Sorman A. H.

THE RURAL-URBAN ENERGY METABOLISM OF CATALUNYA

Scacchi C., Tiruta-Barna L., Benetto E., Loubet P., Jury C., Baudin I.

ASSESSMENT OF DIRECT, INDIRECT AND ECOLOGICAL EXERGY CONSUMPTIONS OF DRINKING WATER PRODUCTION. HOW DOES THE EVALUATION PERSPECTIVE AFFECT THE ENVIRONMENTAL ASSESSMENT?

Paleta R.

MULTI-OBJECTIVE OPTIMIZATION FOR REMOTE AUTONOMOUS ENERGY SYSTEMS

Wächter P., Ornetzeder M., Schreuer A.

CRITICAL ISSUES IN THE SPATIAL ORGANISATION IN THE TRANSITION TO A SUSTAINABLE ENERGY SYSTEM

Ruzzenenti F., Garlaschelli D. and Basosi R.

ON BENEFITS AND PERSPECTIVES OF APPLYING NETWORK THEORY TO ENERGY SYSTEMS

Freire González J.

THE EFFECTS OF ENERGY-SAVING TECHNOLOGICAL CHANGE ON ENERGY CONSUMPTION: ASSESSING THE REBOUND EFFECT

Levin A.

COMMUNICATING EMERGY ANALYSIS AS FOOTPRINT AND EMERGY PROFILE

Pereira L., Zucaro A., Ortega E. and Ulgiati S.

WEALTH, TRADE AND ENVIRONMENT IN BRAZIL AND ITALY. AN EMERGY-BASED COMPARISON OF CARRYING CAPACITY, ECONOMIC PERFORMANCE AND WELLBEING

Nakajima E. S., Gonçalves Pereira L., Ortega E.

SUSTAINABILITY ASSESSMENT FOR IBIUNA COUNTY, SAO PAULO, BRAZIL THROUGH EMERGY EVALUATION

Brown M. T., Protano G., and Ulgiati S.

AN EMERGY ASSESSMENT OF WORLDWIDE BIOGEOCHEMICAL FORMATION OF COAL, OIL AND NATURAL GAS

Takahashi F. and Ortega E.

EMERGY EVALUATION OF AVOCADO CROP AS RAW MATERIAL FOR
BIODIESEL PRODUCTION

ON WHY ARGENTINA IS INCREASING ITS ENERGY INTENSITY: A MULTI-SCALE INTEGRATED ANALYSIS OF ITS ENERGY METABOLISM

Marina Recalde^{*1} and Jesús Ramos-Martín²

¹ *Departamento de Economía, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina. GEPAMA-UBA, Buenos Aires, Argentina*

² *Institute for Environmental Science and Technology (ICTA) and Department of Economics and Economic History, Autonomous University of Barcelona, 08193 Bellaterra, Barcelona, Spain*

ABSTRACT

In this paper we study Argentinean energy consumption pattern for the period 1990-2007, to discuss current and future energy and economic sustainability. To this purpose, we developed a conventional analysis, studying energy intensity, and a non conventional analysis, using the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting methodology. Both methodologies show that the development process followed by Argentina has not been good enough to assure sustainability in the long term. Instead of improving energy use, energy intensity has increased. The current composition of its energy mix, and the recent economic crisis in Argentina, as well as its development path, are some of the possible explanations.

Keywords: Argentina, energy intensity; energy mix; societal metabolism, integrated analysis

JEL Codes: O11, O13, O54, Q01, Q57, Q58

1. INTRODUCTION

The link between energy consumption and economic growth, as well as the relevance of energy for economic development, has been widely studied in the economic literature from both theoretical and empirical standpoints (Asafu-Adjaye, 2000; Tahvonen y Salo, 2001; Smulders y de Nooij, 2003; Toman y Jemelkova, 2003; Van Zon y Yetkiner, 2003; Oh y Lee, 2004; Stern y Cleveland 2004; Lee, 2005; Soytaş y Sari, 2005; Francis et al., 2007; Lee y Chang, 2007; Sari y Soytaş, 2007; Zachariadis, 2007; Apergis and Payne, 2009; Narayan y Smyth, 2009; Bartleet and Gounder, 2010; Tsari, 2010). Understanding this relationship is particularly important from both environmental and socio-economic viewpoints, as energy consumption is crucial to economic development and human environmental impact. This is even more important in developing countries, since energy consumption per unit of output varies through the phases of development (Cleveland, 2003; Stern, 2004).

Argentina has been going through energy supply problems from mid 2004 highly related to economic growth and de-growth periods. Energy supply restrictions were common during the period 2004-2007 and reduced during 2008 and 2009, when the rate of growth of GDP also decreased. However, during winter 2010, industries have faced power shutdowns, both as a result of a very cold winter and the return to the economic growth path. In this frame, the study of the Argentinean energy pattern becomes crucial.

The structure of the rest of the paper is the following: Section 2 studies the relation between energy consumption and Gross Domestic Product (GDP) from a conventional point of view and briefly presents the structure of the energy system and the energy mix.

^{*} Corresponding author; E-mail: mrecalde@uns.edu.ar; m_recalde@hotmail.com; Tel: 0054 0291 4595138

Section 3 presents the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) accounting methodology to analyze the relation; we present the methodology, data and the main results at different hierarchical levels. Finally, Section 4 discusses the results of both sections and draws some final considerations from both methodological and analytical point of view.

2. CONVENTIONAL ANALYSIS: THE ROLE OF ENERGY INTENSITY

2.1. Theoretical aspects

According to the hypothesis of *dematerialization*, there is a reduction in material and energy consumption along the economic growth path. For environmental economists this hypothesis supports the theory of the Environmental Kuznes Curve (EKC), which states the existence of an inverted U-shaped relationship between economic growth and environment degradation. To some extent, the EKC hypothesis is based in the concept of Intensity of Use (Malenbaum, 1978), which means that the consumption of energy and material can be mainly explained by income. The intensity of use concept, as well as the EKC, is supported by three main arguments: *scale* effects, *composition* effects and *technology* effects (Grossman and Krueger, 1991). Therefore, as a joint result of these effects, developed economies should decreased their use of energy per unit of output and they should be dematerializing, while developing ones should be materializing or increasing their energy consumption. However, there are different arguments which confront this theory. One of the most cited considerations is the one stated by Jevons (1990), known as the Jevons Paradox.

If most of these arguments were correct, and in a frame of 'income determinism' (Unruh and Moomaw, 1998) a reduction in energy intensity should be expected in developed and developing economies and an increase should be observed in underdeveloped ones. Some authors insist that this has been the case of many developed economies, especially European countries, related to second oil crisis in middle seventies, and as a result of an active energy policy particularly oriented to reduce energy consumption in industry and household sectors. On the other hand, some others insist that this situation has been mainly related to changes in the quality of the fuels used instead of a reduction in energy consumption per unit of GDP (Cleveland *et al.*, 1984; Kaufmann, 1992).

2.2. Energy Intensity in Argentina

In this section we explore the evolution of energy intensity in Latin America and the Caribbean region and particularly in Argentina in the period 1970-2008. For energy data we used information from OLADE/SIEE, and for monetary data we used statistics from United Nations Statistics Division.

Figure 1 shows the evolution of energy intensity for Argentina. Average primary energy consumption per unit of GDP was around 6.79 MJ per U\$S dollars during the period of analysis, except between 1980 and 1990. Argentina has not achieved to become more efficient in energy consumption; energy intensity in 2007 is the same than in 1979. Energy intensity increased in Argentina during the eighties. The main reason for this increase was the reduction in GDP in U\$S between 1979/80 and 1990. In 1980 the GDP (U\$S) decreased 27% in relation to 1979, while GDP in national currency at 1990 prices reduced only 5% and final energy consumption reduced 0.67%. This implied a 41% of growth in energy intensity, which maintained until 1990 when it decreased 24% in relation to 1989. Once again this can be seen as other accounting artifact. The previously mentioned problems of the Argentine economy (rising fiscal imbalances and expanded domestic debt) exploded as hyperinflation in 1989, when consumer prices rose 4,923.6 % per year. The National Government responded to this situation with economic policies, such as defense of competition, privatization of most of state companies and public

services, changes in the tax system, and the Convertibility Law of March 1991, which established the convertibility of the austral with the U.S. dollar at 10.000:1 respectively (Llach and Cerro, 1998). Therefore, the increase in GDP in U\$S dollars in 1989-1990 can be attributable to the convertibility instead of to a real increase in economic growth. After that period, energy intensity fluctuated while final consumption showed a positive rate of growth except for the period 1999-2001 and 2004. In 2002, in a context of a new socio economic crisis, the Government abandoned this regime. The consequences of this policy were very different for both social and economical development, inflation, inequality in functional income distribution and poverty increased, and therefore energy consumption decreased (Halac and Schmukler, 2003; Nataraj and Sahoo, 2003; Lindenboim *et al*, 2005; Zaza, 2010). After that period, from 2004 on, economic growth increased at *Chinese growth rates*. However, energy consumption reduced in several sub periods from 2004 on as a result of supply restrictions due to national energy crises and power shutdowns. This situation is mainly explained as a joint effect of lack of energy investments during the previous period and a sudden increase in energy demand because of increases in economic growth, which implied that energy supply could not correctly respond.

Figure 1. Energy Intensity of Argentina. 1970-2007



Source: Own elaboration on basis of data from OLADE/SIEE

3. MULTI-SCALE INTEGRATED ANALYSIS OF SOCIETAL AND ECOSYSTEM METABOLISM

3.1. Methodology

The Multi Scale Integrated Analysis of Societal and Ecosystem Metabolism developed by Giampietro and Mayumi (1997, 2000) and Giampietro (2003) integrates different fields of study with the purpose of a wide analysis of the social and economic and ecological system. This method has been developed for different countries and regions such as Spain, Catalonia, Ecuador, Vietnam and China ((Falconi-Benitez, 2001; Ramos-Martin, 2001; Ramos-Martin and Giampietro, 2005; Eisenmenger *et al.*, 2007; Ramos-Martin *et al.*, 2007; Giampietro *et al.*, 2009; Sorman, 2009). The “metabolism of human society” is a notion used to characterize the processes of energy and material transformation in a society that are necessary for its continued existence (Ramos-Martin *et al.*, 2007). In some way this methodology is an application of the Georgescu-Roegen (1984) flow-fund model, which is also a representation of an economic-social-biophysical system².

The use of the MuSIASEM has several advantages in comparison to the conventional analysis. As the study can be developed at different hierarchical levels, MuSIASEM permits a deeper and richer analysis than conventional studies. The division of the human time allocation between the dissipative and hyper cycle sectors in a society,

² For a more complete description of the fundamentals of the MuSIASEM see Gowdy *et al* (2007), Ramos-Martin *et al.* (2007) and Giampietro *et al.* (2009).

can be made through the division of the activities between the productive paid work (PW) and the consumption non- paid work (HH) sectors.

As previously mentioned, the MuSIASEM can be made at different hierarchical levels, therefore the different aspects which coordinate the evolution of the system and be clearly understood. There are three hierarchical levels of study: the national global level (n); the division between productive and consumption activities (PW and HH) (n-1); and then the study of the main productive subsectors is made in the context of the PW sector (n-2). There are three main subsectors, which include an aggregation of some other more specific activities. The Productive Sector (PS), including energy, building and manufacturing, Service and Government (SG), and Primary Sector (AG), including agriculture, husbandry, forests and hunting.

3.2. Description of variables

Variables can be divided into two main groups: extensive variables, which can be summed up and characterized the size of the system; and intensive variables (indicators) which characterize changes in the system. Within the extensive variables we find:

GDP: Gross Domestic Product

THA: *Total Human Activity*: Total human time a society has available for conducting different activities (endosomatic and exosomatic consumption), measure in hours (h). (Population times 8760h)

HA_{PW}: *Human Activity paid work*: Human time in the productive sector in one year, measure in hours (h).

HA_{HH}: *Human Activity households*: Human time in the households in one year, measure in hours (h).

$$HA_{PW} = \sum HA_i$$

$$HA_i = W * PO_i * HsS_i$$

Where:

HA_i: Total human activity for the activity *i*.

W: Working weeks per year

PO_i: Population occupied in the activity *i*.

HsS_i: Weekly hours of work in the activity *i*.

$$THA = HA_{PW} + HA_{HH}$$

TET: *Total Exosomatic Throughput*: Total primary energy dissipated in a socio-economic system for supporting consumption and production activities in one year, measured in Joules (J).

ET_{PW}: *Exosomatic Throughput paid work*: Total primary energy used in the paid-work sector in one year.

ET_{HH}: *Exosomatic Throughput households*: Total primary energy used in the household sector in one year.

$$TET = ET_{PW} + ET_{HH}$$

Within indicators or intensive variables we have:

$EMR_{SA} = \frac{TET}{THA}$: *Average Exosomatic Metabolic Rate*: Energy consumption per hour of human time available to the society.

$EMR_{PW} = \frac{ET_{PW}}{HA_{PW}}$: *Paid Work Exosomatic Metabolic Rate*: Energy consumption in the paid-work sector per working hour available.

$EMR_{HH} = \frac{ET_{HH}}{HA_{HH}}$: *Household Exosomatic Metabolic Rate*: Energy consumption in the household sector per household hour available.

$ELP_i = \frac{GDP_i}{HA_i}$: *Economic Labour Productivity*: Added value per hour of working time in sector i .
 $\frac{ELP_i}{EMR_i} = \frac{PBI_i}{ET_i}$: *Energy Efficiency of Production*: Added value generated per unit of energy consumption in sector i , measured in dollars/Joules.

3.3. Data used in the analysis

The period of analysis is 1990-2007 and the main data sources have been national statistics when available, international sources otherwise. Energy data has been obtained from the Energy Balances of the Secretaría de Energía de la Nación 1990-2007. For the demographic data we used national statistics from the Instituto Nacional de Estadísticas y Censos (INDEC)³ and International Labor Organization (ILO) -LABORSTA⁴. Regarding monetary data we used statistics from United Nations Statistics Division⁵ and INDEC.

For monetary information in the n-2 level we used Gross Value Added by kind of economic activity at constant (1990) prices in US dollars from *United Nations Statistics Division; National Accounts Estimates of Main Aggregates*⁶.

Following Ramos-Martin (2001) and Ramos-Martin et al. (2007) ET_{HH} has been calculated as residential energy consumption plus 25% of transport energy consumption; and the remaining 75% of transport energy consumption has been allocated to services and government sector. We assumed that 50% of mobility is for transporting goods; 50% of the remaining half corresponds to compulsory mobility and the other 50% corresponds to voluntary mobility which we incorporate to household energy consumption. In the same line, the Gross Value Added (GVA) generated in the transport sector has been allocated to SG. THT and HA_i estimations were based on estimations and projections of population and rate of activity evolution from INDEC. To compute the occupation rate by industry we extrapolate INDEC data for Censo Nacional de Población y Vivienda 1991 and 2001. In order to complete the information we used data from ILO-LABORSTA and CEPAL-CEPALSTAT. We assume a total of 48 weeks of working time in a year. We combined this information with the average working hours per week by economic sector from data from ILO-LABORSTA. The average working hours per week during the period of analysis has been 48.5, 43.27 and 38 for the AG, PS and SG, respectively.

3.4. Results

3.4.1. Level n: Argentina

The first result we found is a high correlation between energy consumption and GDP during 1990-2007. During the period of analysis, energy consumption and GDP have a similar evolution as well as similar cyclical changes. Secondly, primary energy intensity, energy consumption and GDP are highly related. As displayed in **Figures 4 and 5**, while energy intensity has an N shape, energy consumption grew during the period of analysis and there are three turning points for energy intensity. Thirdly, energy consumption and population move together as shown in **Figure 6**. As population grows so does energy consumption. This relation shows that increases in energy consumption have been devoted, partially, to cover population growth with a minimum of energy consumption. We found that, in some way energy per person has grown in the past two decades, which may be indicating that population material standard of life is increasing. However, we will come back to this discussion later.

³ <http://www.indec.gov.ar/>

⁴ <http://laborsta.ilo.org/>

⁵ <http://unstats.un.org/unsd/default.htm>

⁶ It is important to point out that there may be a methodological mistake as we computed GVA instead of GDP. However, this is the only available information at sectorial level in US dollars at constant prices.

The average exosomatic metabolic rate of the society (EMR_{SA}) exhibits a positive trend, which oscillates between 8.20 and 11.47 MJ/h. From this information, energy consumption per hour in Argentina is larger than two of its neighbors. According to Eisenmenger *et al.* (2007) in 2000 while Brazilian and Chilean EMR_{SA} was 5.21 MJ/h and 7.60 MJ/h respectively, in Argentina it was 9.25 MJ/h, and in Venezuela 11.21MJ/h. However, these disparities can be found all around the world, as world average rate is 7.8MJ/h, while OECD is 22.3 MJ/h and, in 1999, the Chinese EMR_{SA} was 4.1 MJ/h (Gowdy *et al.*, 2009).

Figure 3. TET and GDP evolution. 1990-2007

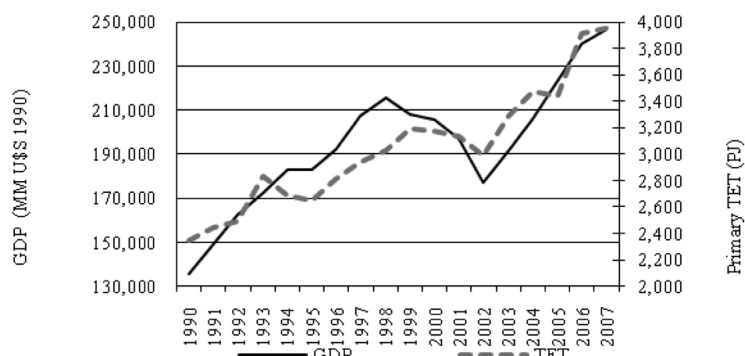


Figure 4. TET and EI evolution. 1990-2007

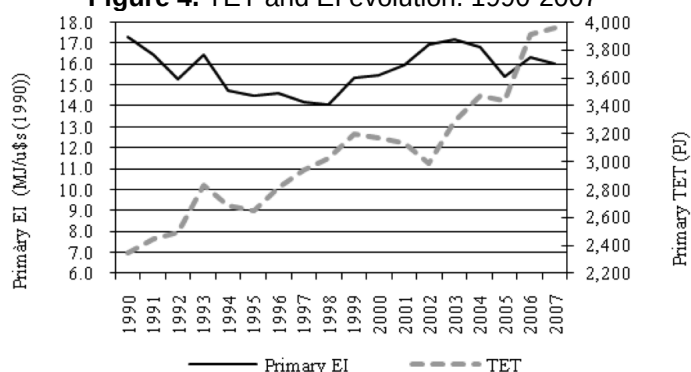


Figure 5. EI and GDP evolution. 1990-2007

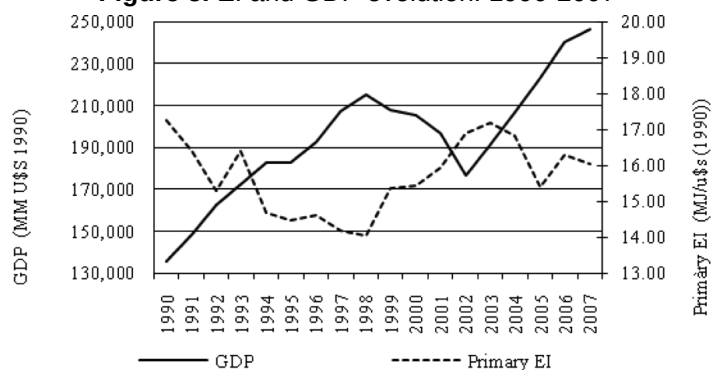
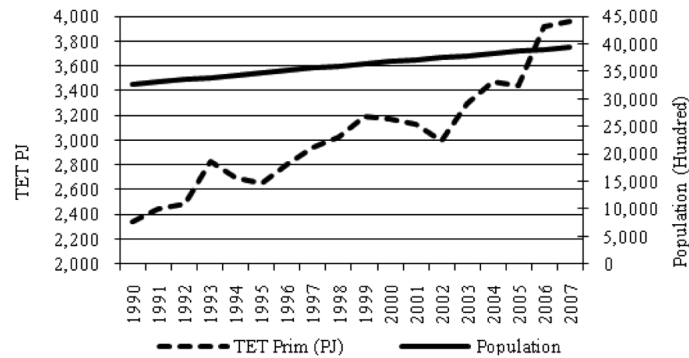


Figure 6. Population and TET evolution. 1990-2007



3.4.2. Level n-1: production and consumption

As previously mentioned TET has a smooth positive trend, which can be explained through the study of the production side (PW) and consumption side (HH). At this level of analysis, we found that while there is a positive trend in ET_{PW} , the ET_{HH} fluctuates and has recently diminished. Particularly, there is a decline in ET_{HH} from 2003/04 to 2006/07 and a 12% of increase in ET_{PW} between 2005 and 2006. This is one of the most interesting results we found. Most of the countries may reduce EMR_{HH} as a result of population growth or PW capitalization, but, if ET_{HH} decreases absolutely the country faces a huge structural adjustment in energy consumption. In a similar way, the increase in the exosomatic metabolic rate in the productive and dissipative sectors has been very different. At the n level, EMR_{SA} increased 39% between 1990 and 2007. In the same period, the increase in EMR_{HH} was about 44%, while in EMR_{PW} was 128%. Once again, the increase in the metabolic rate of the productive sector could be an indicator of the capitalization of the economy. Simultaneously, the increase in energy consumption per working hour, and therefore in capital in the economy, may increase working productivity.

3.4.3. Level n-2: evolution of the productive sector

The first result to highlight is the low share of HA_{AG} mainly due to the small proportion of active population working in primary sector. This situation may imply a trend to the mechanization of the primary sector, which necessarily implies an increase in capitalization. Nevertheless, the evolution of ET_{AG} and EMR_{AG} along the period under analysis has been erratic. There may be a capitalization of the sector up to 2004, particularly in 2001-2004, and a recent fall. This may be explained as a result of the economic and monetary context after 2001, which was favorable to exports sectors in which the agricultural one plays a key role. Furthermore, the evolution of energy consumption in primary sector increased between 2004 and 2005, and therefore the EMR_{AG} augmented. This increase in energy consumption has been mainly due to a 57% in the Diesel Oil and Gas Oil consumption and a 100% increase in Fuel Oil.

Secondly, the lower share of the HA_{AG} in relation to the SG and PS sectors, may imply, not only a primary sector mechanization trend, but also a change of the Argentinean economy to industrial and service sectors. Then, as a result of a small share of working population in the primary activities, there is a high level of energy metabolic rate, particularly in comparison to Brazil and Chile.

4. CONCLUDING REMARKS

The use of the MuSIASEM complements the completely economic conventional view of energy intensity as it allows us to study different dimensions of the reality such as economic productivity and competitiveness, quality of life and equality, and environmental impact of natural resources. As stated by Gowdy *et al.* (2009) the relationships between human activity, energy use and economic production derived from this approach help on comparative economic systems and the historical development of different economies.

In the Argentinean case, the erratic evolution of energy intensity shows that increases in energy consumption did not implied efficiency increases. According to Altomonte (2009) productive structure, sector consumption composition and the particular share of energy fuels in the energy mix are the main reasons to explain the non desirable path of energy intensity in Latin American region, this seems to be also the case of Argentina.

As well as the global dependence on exosomatic energy consumption, the country has a high metabolic rate in the different productive sectors. This fact is significantly different to the results obtained by Eisenmenger et al. (2007) for some countries of the Latin-American region, according to which primary energy is less energy dependent. The SG sector presents a high energy consumption level, similar to Venezuela and very superior to China, Brazil and Chile.

One of the main conclusions driven from the results emphasizes the similarities between Argentinean and Venezuela social metabolic patterns. However, on the basis of these similarities the energy perspectives are different for both countries. While Venezuela hydrocarbons proven reserves are significantly important (87.04 Gbbl of oil and 4708 Gm³ of natural gas), the Argentinean ones are lower (2.59 Gbbl of oil and 446.16 Gm³ of natural gas).

Moreover, in a context of diminishing of hydrocarbons reserves, which represent 89% of TPES in Argentina, and energy supply problems, the energy pattern showed by Argentina show a lack of sustainability of its energy policy in both the medium and long term.

ACKNOWLEDGEMENTS

Marina Recalde would like to thank the Departamento de Economía of the Universidad Nacional del Sur, Argentina and Dr. Walter Pengue, GEPAMA-UBA and ALFA – SUPPORT program, for the financial support for a research stay at the ICTA-UAB, where this study was mainly carried on. Jesús Ramos-Martin acknowledges support from: (i) the Consolidated Research Group on “Economic Institutions, Quality of Life and the Environment”, SGR2009–00962; (ii) the EU funded project “Synergies in Multi-Scale Interlinkages of Eco-Social Systems” (SMILE, Contract 217213-FP7-2007-SSH-1), and (iv) the Spanish Ministry for Education project HAR-2010-20684-C02-01.

REFERENCES

- Altomonte, H. 2009. “Eficiencia energética en América Latina y el Caribe: situación y Perspectivas, *Conferencia Regional Intergubernamental sobre Eficiencia Energética, CEPAL, OLADE, GTZ*.
- Apergis, N. Payne, J. 2009. “Energy consumption and economic growth: Evidence from the Commonwealth of Independent States”. *Energy Economics* 31 641–647
- Asafu-Adjaye, J. 2000 “The relation between energy consumption, energy prices and economic growth: time series evidence from Asian developing countries”, *Energy Economics* 22, 615-625.
- Bartleet, M., Gounder, R. 2010. “Energy consumption and economic growth in New Zealand: Results of trivariate and multivariate models”, *Energy Policy* 38, 3508–3517
- Beaudreau, B. 2005. “Engineering and economic growth”, *Structural Change and Economic Dynamics* 16, 211-220.
- Cleveland, C. 2003. *Biophysical constraints to economic growth. Encyclopedia of Life Support Systems*, (EOLSS Publishers Co. Oxford, UK).
- Cleveland, C., Costanza, R., Hall, C. Kaufmann, R. 1984. “Energy and the U.S. Economy: A Biophysical Perspective”. *Science* 31 (225) 890 – 897.
- Eisenmenger, N., Ramos Martín, J., Schandl, H. 2007 “Análisis del metabolismo energético y de materiales de Brasil, Chile y Venezuela”, *Revista Iberoamericana de Economía Ecológica* 6, 17-39

- Eldridge, N., & Gould, J. S. 1972. "Punctuated Equilibria: An Alternative to Phyletic Gradualism". In T.J.M Schopf (Ed.): *Models in paleobiology*. San Francisco: Freeman, Cooper and Co.
- Francis, B., Moseley, L., Osaretin Iyare, S. 2007 "Energy consumption and projected growth in selected Caribbean countries", *Energy Economics* 29, 1224-1232.
- Georgescu-Roegen, N. 1971. *The entropy law and the economic process*. Cambridge, Mass, Harvard University.
- Gowdy, J., Giampietro, M., Ramos-Martin, J., Mayumi, K. 2009 "Incorporating biophysical foundations in a hierarchical model of societal metabolism", *Post Keynesian and Ecological Economics: Confronting Environmental Issues*, Edward Elgar.
- Gowdy, J.M. 1994 *Coevolutionary economics: The Economy, Society, and the Environment*. Dordrecht: Kluwer Academic Publishers.
- Halac, M.; Schmukler, S. 2003. "Distributional Effects of Crises: The Role of Financial Transfers" (May 15, 2003). *World Bank Policy Research Working Paper No. 3173*.
- Kaufmann, R. 1992. "A Biophysical analysis of the energy/real GDP ratio: implications for substitution and technical change". *Ecological Economics* 6 (1) 35-56.
- Lee, C. 2005 "Energy consumption and GDP in developing countries: A cointegrated panel analysis", *Energy Economics* 27, 415-427.
- Lindenboim, J.; Graña, J.; Kennedy, D. 2005. „Distribución funcional del ingreso en Argentina. Ayer y hoy". *Documentos de Trabajo 4, Centro de Estudios sobre Población, Empleo y Desarrollo (CEPED)*.
- Llach, J.; Cerro, F. 1998 "The third stage of Argentine Economic Growth". *Argentina: the challenges of modernization*. Towman & Littlefield.
- Luzzati, T., Orsini, M., 2009. "Investigating the energy-environmental Kuznets curve". *Energy* 34, 291-300.
- Narayan, PK; SMYTH, R. (2009), "Multivariate granger causality between electricity consumption, exports and GDP: Evidence from a panel of Middle Eastern countries". *Energy Policy*, 37 (1), 229-236.
- Nataraj, G.; Sahoo, P. 2003. "Argentina's Crisis: Causes and Consequences", *Economic and Political Weekly Vol. 38 (17) (Apr. 26 - May 2, 2003), pp. 1641-1644*
- Oh, W. y Lee, K. 2004 "Causal relation between energy consumption and GDP revisited: the case of Korea 1970-1999", *Energy Economics* 26, 51-59.
- Panayotou, T., 1993. "Empirical tests and policy analysis of environmental degradation at different stages of economic development". *Working Paper, Technology and Environment Programme, International Labour Office, Geneva*
- Ramos-Martin, J., 2001 "Historical Analysis of Energy Intensity of Spain: From a "Conventional View" to an "Integrated Assessment"", *Population and Environment: A Journal of Interdisciplinary Studies* 22 (3), 281-313.
- Ramos-Martin, J. 2005 *Complex systems and exosomático energy metabolism of human societies*. Universitat Autònoma de Barcelona.
- Ramos-Martin, J., Cañellas-Boltà, S., Giampietro, M., Gamboa, G. 2007 "Catalonia's energy metabolism: Using the MuSIASEM approach at different scales", *Energy Policy* 37, 4658–4671.
- Recalde, M., Zilio, M. 2009. "Curva de Kuznets Energético-Ambiental: Evidencia para América Latina". *Anales de la XLIV reunión de la Asociación Argentina de Economía Política*.
- Smulders, S. y Nooij, M. 2003 "The impact of energy conservation on technology and economic growth", *Resource and Energy Economics* 25, 59-79.
- Sorman A., Giampietro, M., Lobo A., Serrano, T. 2009. "Applications of the MuSIASEM approach to study changes in the metabolic pattern of Catalonia", *Reports on Environmental Sciences* 4.
- Soytas, U. y Sari, R. 2007 "The relation between energy and production: Evidence from Turkish manufacturing industry", *Energy Economics* 29, 1151-1165.
- Stern, D. 1997. "Limits to substitution and irreversibility in production and consumption: a neoclassical interpretation of ecological economics", *Ecological Economics* 21, 197-215.
- Stern, D., 2004. "Elasticities of Substitution and Complementarity". *Working Papers in Economics*
- Stern, D. y Cleveland, C., 2004 "Energy and economic growth", *Rensselaer Working Papers in Economics* 0410
- Tahovnen, O. y Salo, S. 2001 "Economic growth and transitions between renewable and non renewable energy resources". *European Economic Review* 45, 1379-1398.
- Toman, M.A., Jemelkova, B., 2003. "Energy and economic development: an assessment of the state of knowledge". *Energy Journal* 24 (4), 93–112.

- Tsani, S. 2010. "Energy consumption and economic growth: A causality analysis for Greece", *Energy Economics* 32, 582–590.
- Unruh, G.C. Moomaw, W.R. 1998. "An alternative analysis of apparent EKC-type transitions", *Ecological Economics*, vol. 25, 221-229.
- Van Zon, Y. 2003 "An endogenous growth model with energy saving technical change", *Resource and energy economics* 25, 81-103.
- Zachariadis, T. 2007 "Exploring the relationship between energy use and economic growth with bivariate models: New evidence from G-7 countries", *Energy Economics* 29, 1223-1253.
- Zaza, R. 2010. *Argentina 2001-2009: From the financial crisis to the present*.

THE RURAL-URBAN ENERGY METABOLISM OF CATALUNYA

Pere Ariza-Montobbio and Alevgul H. Sorman*

ICTA-UAB, Spain

ABSTRACT

Building upon the previous applications of the MuSIASEM approach applied to analysing the energetic metabolism of Catalonia; this study further investigates the rural-urban divide of the energetic throughput within the Catalan Society. The methodological analysis implies the definition of several household typologies divided among a territorial zone encompassing the rural urban divide. The energy metabolic rate (EMR – the energy consumption per hour) of different typologies of rural and urban households are analysed within different zonal typologies to ultimately analyse the differing patterns of bio-economic pressure (BEP) yielded per hectare of this urban- rural divide (depending on the characteristics of the households of each zone). The composition of this rural-urban mix of different household typologies of different regions of Catalonia, revealing different metabolic profiles can then be used to investigate the performance of the Catalan society. Its relation with the metabolism of the rest of the territory at a larger scale helps to provide a more refined and transparent information for decision making. Particularly, it helps to inform the option space for Catalonia energy planning, the ongoing controversies of which energy infrastructures promote and where to locate them and the ongoing debate on the fuzziness between rural and urban areas.

Keywords: MuSIASEM, Household metabolism, Bio-Economic Pressure, rural-urban metabolism

* Presenting author: Pere Ariza-Montobbio (pere.ariza@uab.cat)

ASSESSMENT OF DIRECT, INDIRECT AND ECOLOGICAL EXERGY CONSUMPTIONS OF DRINKING WATER PRODUCTION. HOW DOES THE EVALUATION PERSPECTIVE AFFECT THE ENVIRONMENTAL ASSESSMENT?

Costanza Scacchi¹, Ligia Tiruta-Barna², Enrico Benetto^{*1}, Philippe Loubet^{1,2}, Colin Jury¹, Isabelle Baudin³

¹ *Public Research Centre Henri Tudor / Resource Centre for Environmental Technologies, 66 rue de Luxembourg, L-4002, Esch sur Alzette, Luxembourg,*

² *Université de Toulouse; INSA, UPS, INP; LISBP, 135 Avenue de Rangueil, F-31077 Toulouse ; INRA, UMR792, Laboratoire d'Ingénierie des Systèmes Biologiques et des Procédés, F-31400 Toulouse ; CNRS, UMR5504, F-31400 Toulouse, France*

³ *Suez Environnement ; 38 rue du président Wilson, F-78230 Le Pecq, France*

ABSTRACT

In this study novel energy assessment perspectives are applied to the environmental assessment of drinking water production plants. The novelty of the application consists in a conventional LCA combined to the assessment of the Ecological Cumulative Exergy Consumption – ECEC methodology (an emergy based methodology to include the role of supporting ecosystem services) within state of the art LCA software (Umberto®) and database (Ecoinvent®).

Keywords: LCA, Life Cycle Assessment, emergy, energy, ecological exergy, resources, water

1. INTRODUCTION AND GOAL

Based on the LCI results of a given process, the natural resource consumption can be evaluated nowadays by a set of indicators as defined within the known assessment methods. Traditionally, the non renewable resources (including fossil fuels) are evaluated for their availability from an economic perspective. In these assessment methods commonly used with LCA, non-renewable resource depletion is represented by characterisation (or damage) factors like the abiotic depletion potential (ADP in kg-eq Sb, CML method) or as supplementary energy necessary to ensure the future extraction of the remained resource (in MJ, EcoIndicator99 method). One of the limits of above mentioned methods is they don't consider renewable resources (except energetic resources), for example water resources. More recent evaluation methods focus on the quality of resources not only on their abundance and consequently are compatible with renewable resources consideration in the global assessment. It is the case of Cumulated Exergy Demand CExD indicator, henceforth included in Ecoinvent LCA data base.

These approaches tackle any production system as isolated from surrounding ecological services, which are considered to be constant reservoir and therefore neglected. Changes have been observed in natural cycles and ecosystems, proving that this assumption is not always true (Millennium Ecosystem Assessment, 2010). Ecological inputs have been estimated to be twice as valuable as the global national product (Costanza et al, 1997) as well, so that accounting for these environmental services,

* Corresponding author: E-mail: enrico.benetto@tudor.lu

normally neglected, is a reasonable option. The adoption of ecological exergy (Yi et al, 2010a, 2010b) and emergy-based environmental accounting methods as a complementary decision making tool has been suggested by the scientific community.

The concept of so called ECEC (Ecological Cumulative Exergy Consumption) has been introduced by Hau (2002). It represents an expansion of CExC (Cumulative Exergy Consumption) to include the energy used up by ecological processes. This method is supposed to include a complementary “nature perspective” in LCA.

In this study these different perspectives are applied to the environmental assessment of drinking water production plants. The novelty of the application consists in a conventional LCA combined to the assessment of the Ecological Cumulative Exergy Consumption – ECEC methodology (a slightly modified form of emergy method) within state of the art LCA software (Umberto®) and database (Ecoinvent®).

The final aim of the study is to evaluate under the same perspective both fossil and renewable resources and to analyze the additional information that come from the combined use of emergy and LCA. The application to drinking water production is particularly useful since it highlights the importance to account for ecological services related to water resources as compared to conventional assessment of fossil resources.

2. METHODOLOGY

The first step of the assessment is the mass and energy inventory building for the studied systems over their life cycles and within well defined boundaries. An industrial process life cycle is composed of 3 stages: plant construction, functioning period and deconstruction. The application study was realised on 2 plants for potable water production situated in France. Only the functioning period is considered here while it is the most impacting life cycle stage. The inventory is based on data collected on industrial sites, data from plant design and data from Ecoinvent for the background processes. The LCI was obtained using Umberto software and referred to the functional unit of 1m³ of potable water produced. So a list is obtained comprising resources consumed for plant functioning including direct used resources (river water for instance and some fossil fuels) and resources consumed in background processes for chemicals production, electricity production, etc.

The LCI is then the basis for natural resources consumption evaluations by three methods: cumulated energy demand CED as classical energy consumption evaluation, cumulated exergy demand CExD and ecological cumulated exergy consumption ECEC. CED and CExD evaluation methods are included in Ecoinvent, while ECEC is the new alternative method implemented here. LCI coupled ECEC is an ecological based LCA approach (Yi et al, 2010b).

2.1 Cumulated energy demand (CED)

CED indicator groups all forms of energy used expressed in their net energy content relative to the form of energy supplied (heat, potential, kinetic, etc.). The categories included in Ecoinvent data base are: biomass, fossil, geothermal, nuclear, primary forest, solar, water, wind, geothermal.

2.2 Cumulated exergy demand (CExD)

CExD measures the exergy consumption in the industrial systems over the life cycle. It is a useful indicator because it evaluates the same parameter for any stream, i.e. the useful work extracted from the stream (system) in its environment, which is the finality of all processes. It allows then comparisons between all types of resources. Total exergy of a stream is composed of chemical, physical, potential, kinetic and nuclear exergy.

Using exergy allows putting together in a unified unit (J) the information about the available for use *quality* and *quantity* of a resource.

In this study the CExD indicator is used as it exists in Ecoinvent data base. The impact category indicator comprises eight resource categories: biomass, fossil, metals, minerals, nuclear, primary forest, solar, water, water resources, wind.

2.3 Ecological cumulated exergy consumption (ECEC)

ECEC is an ecological based LCA approach, as stated by Yi et al (2010b). ECEC is analogous to the concept of emergy but does not rely on any of its controversial claims. ECEC becomes equivalent to emergy just under certain conditions. Allocation of ECEC is different from emergy analysis, connecting it with standardized approach in LCA. The principle of the LCI based ECEC developed here is explained in Figure 1. The algebra and allocation rules are those of mass and energy inventories in Ecoinvent. The resource consumption balance is then used by applying appropriate transformity values for each resource. The result is translated in emergy of resources consumed by the life cycle of a system. This method doesn't allow calculation of the emergy of intermediary and final products, but give information about the environmental services contribution for processing these products.

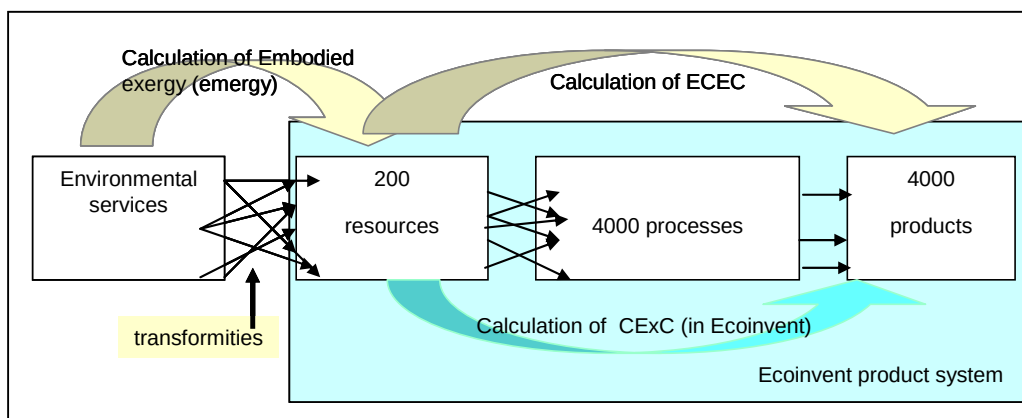


Figure 1. Principle of ECEC calculation

Thus, to calculate ECEC, resources' transformity values are needed to be applied to the inventory data.

Water resources : there are several water resources used over the process life cycle; for instance the main resource used for potable water production (rivers located in France) and generic water resources used in background processes (electricity production, chemicals production, etc.). Emergy and transformity of main river resource was calculated following the method described by Odum (1996). The formula of Gibbs free energy (G) was applied knowing the total dissolved solids for local resources. Then the local factors contributing to the water emergy were evaluated (sun wind, rain, geothermal heat) and combined for river water emergy calculation (E_m). River local transformity is given by $T = E_m / G$. Transformity (J/m^3) of other type of water resources (non local) were derived from Buenfil (2001). ECECs of different water resources were then calculated by $ECEC = T \times \text{Volume}$.

Energy resources: the energy resources, i.e. biomass, wood, kinetic in wind, potential in hydropower, (MJ) have been multiplied by the most appropriate transformity values taken from (Odum et al, 2000 Folio #1; Odum, 2000 Folio #2, Odum 1996). No data have been found for nuclear energy.

Fossil fuels (oil, natural gas and coal) transformities were taken from the same literature references.

Land occupation and transformation: the same transformity was used for both categories (land sustained, Odum, 2000 Folio #2).

Metals and minerals: A wide list of minerals and metals elements is available in Ecoinvent. To associate them appropriate transformity values, instead of using an average number, we based our assumption on the work by Cohen et al (2007) in which the authors evaluate unit emergy values (seJ/g) for 26 crustal elements based on published ore grade cut-off (OGC), so that transformity values are scaled to ore grade; they also extended the assumption to a list of 26 remaining elements for whom OGC is not available, developing a predictive model that relates the OGC value to its crustal abundance and price. Where available, we associated the transformity value from Cohen et al (2007), in some cases grouped some materials on the basis of their composition on certain elements. For those elements where no transformity values were available we assumed an average value of $1.79 \cdot 10^9$ seJ/kg.

Rocks: A list of rocks is generated by Ecoinvent. To group them in categories with known transformity is not often easy. So, we associated to shale, clay and kaolinite the transformity of shale, as they are very common in this kind of sedimentary rock. For sand and gravel we used the transformity of sandstone; for basalt that of volcanic rock (as it is an exhaustive volcanic rock).

For those elements where no transformity values were available we assumed an average value of $1.76 \cdot 10^8$ seJ/kg.

3. CASE STUDY: DRINKING WATER PRODUCTION PLANTS

3.1. Site A

This plant is located in North France and uses river water. Two pump stations are present on site for resource take and treated water distribution. The treatment is realised in two lines, which have exactly the same steps. Figure 2 shows the scheme of one treatment line. The plant consumes electricity, chemical reagents injected at different points on the process chain, and produces the needed ozone on site. Chemical reagents used: lime, liquid CO_2 , KMnO_4 , coagulant iron chloride and polymers, PAC (powdered activated carbon), sulphuric acid (98%), bleach, soda.

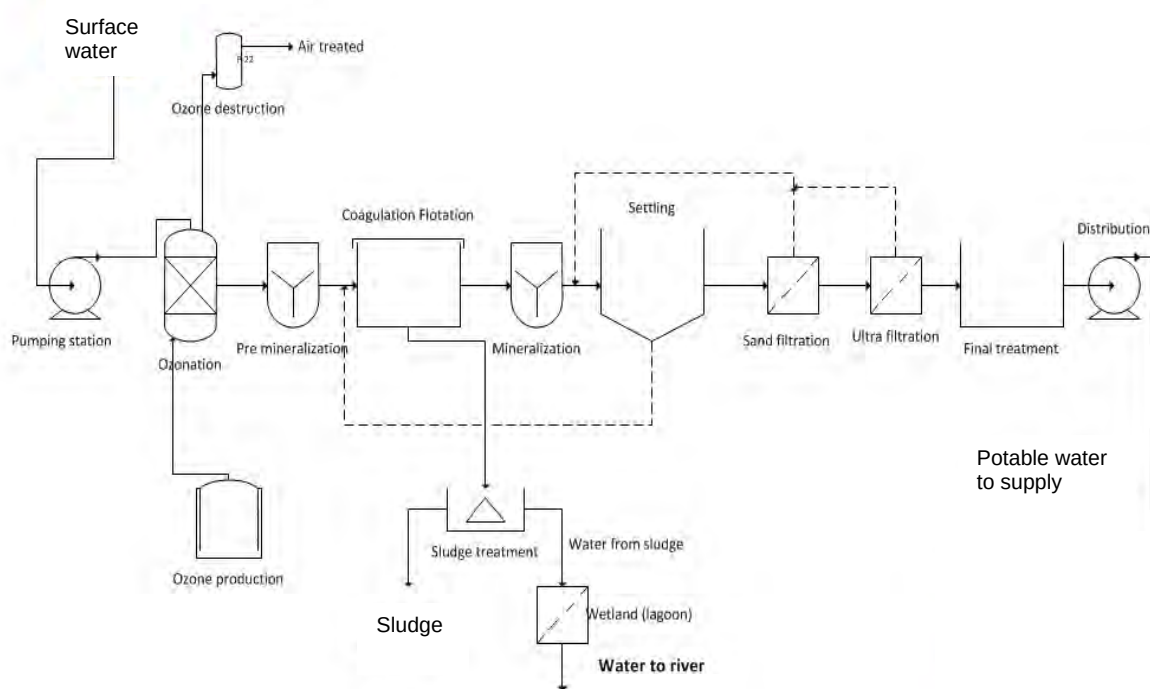


Figure 2. Scheme of one treatment line of plant A.

3.2. Site M

Plant M is one of the most productive in the Paris area and uses Seine water as resource. Figure 3 shows schematically the treatment process. It is composed by 3 treatment lines, with different designs and productivities. Besides electricity and few fossil fuels, the plant consumes a set of chemical reagents: sulphuric acid (98%), aluminium sulphate (liquid at 8.2%) and polymer (ASP25) used for the coagulation-flocculation, PAC and GAC (powdered and granular activated carbon), chlorine for pre-chlorination and disinfection, soda for pH control, lime for sludge treatment. The plant is equipped with ozone generators. The raw water is supplied by gravity from the Seine to the bar screen, followed by sieving and then a stock tank (with pre-chlorination), from which the water is pumped to the treatment phase in the three lines. All other reagents are injected in different places following the unit process design and resource water quality.

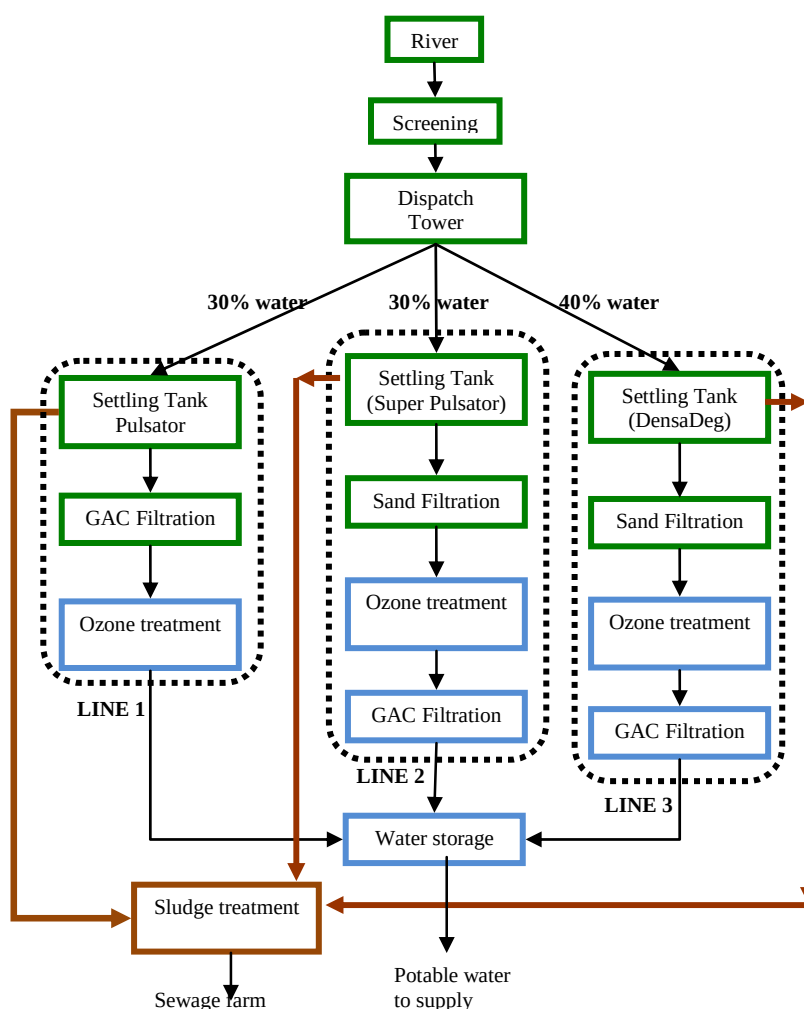


Figure 3. Scheme of site M

4. RESULTS AND DISCUSSION

The list of resources was aggregated in categories in order to compare three evaluation methods: CED, CExD and ECEC (tables 1 and 2). A comparison of the 2 plants could be made with respect to two indicators for resource consumption metrics (Yi et al, 2010b):

- Renewability Index (RI) is the ratio of the consumption of renewable resources to total consumption.

- Resource Intensity (R) represents cumulative resource consumption per unit of product.

Several remarks stand out from the above results.

CED evaluates only energetic resources (non-renewable and renewable); no renewable resources used as materials are evaluated. CExD evaluates also materials, more exactly the useful part of the energetic content in relation with the reference environment. One observes that the MJ-eq values of energetic resources are very similar between CED and CExD. At this point, CExD-CED represents the contribution of non-energetic materials, which is dominated by the water resources.

Table 1. Evaluation results for site A (for 1m³ potable water production)

Resource	ECEC (MseJ)	CExD (MJ-eq)	CED (MJ-eq)
Water resources	$9.96 \cdot 10^4$	$5.20 \cdot 10^1$	-
Wind	23.0	$2.34 \cdot 10^{-2}$	$2.34 \cdot 10^{-2}$
Solar	$2.82 \cdot 10^{-4}$	$2.62 \cdot 10^{-4}$	$2.82 \cdot 10^{-4}$
Primary forest	(in biomass)	$6.04 \cdot 10^{-6}$	$5.75 \cdot 10^{-6}$
Hydropower	$1.26 \cdot 10^5$	$4.73 \cdot 10^{-1}$	$4.73 \cdot 10^{-1}$
Nuclear	(not available)	8.77	8.77
Wood/biomass	$6.36 \cdot 10^3$	$2.64 \cdot 10^{-1}$	$2.52 \cdot 10^{-1}$
Land	$1.88 \cdot 10^3$	-	-
Fossil fuels	$2.18 \cdot 10^5$	4.61	4.66
Crustal elements	$1.61 \cdot 10^2$	-	-
Metals	(in crustal elements)	$1.51 \cdot 10^{-1}$	-
Minerals	(in crustal elements)	$3.43 \cdot 10^{-2}$	-
R	$4.53 \cdot 10^5$	6.63·10	$1.42 \cdot 10^1$
R(CExD)-R(CED)		52.1 (≅water)	
RI	0.52	0.80	0.05

Table 2. Evaluation results for site M.(for 1m³ potable water production)

Resource	ECEC (MseJ)	CExD (MJ-eq)	CED (MJ-eq)
Water resources	$5.58 \cdot 10^4$	$5.23 \cdot 10^1$	-
Wind	4.71	$4.64 \cdot 10^{-3}$	$4.64 \cdot 10^{-3}$
Solar	$2.28 \cdot 10^{-5}$	$1.92 \cdot 10^{-5}$	$2.07 \cdot 10^{-5}$
Primary forest	(in biomass)	$6.73 \cdot 10^{-6}$	$6.41 \cdot 10^{-6}$
Hydropower	$7.39 \cdot 10^4$	$2.76 \cdot 10^{-1}$	$2.76 \cdot 10^{-1}$
nuclear	(not available)	6.43	6.43
Wood/biomass	$1.02 \cdot 10^3$	$4.25 \cdot 10^{-2}$	$4.25 \cdot 10^{-2}$
Land	$3.92 \cdot 10^2$	-	-
Fossil fuels	$4.13 \cdot 10^4$	1.06	1.07
Crustal elements	$9.37 \cdot 10^1$	-	-
Metals	(in crustal elements)	$3.42 \cdot 10^{-2}$	-
Minerals	(in crustal elements)	$4.73 \cdot 10^{-3}$	-
R	$1.72 \cdot 10^5$	$6.02 \cdot 10^1$	7.81
R(CExD)-R(CED)		52.39 (≅water)	
RI	0.76	0.87	0.04

ECEC takes into account the embodied energy in the materials, not only the actual exergetic content. These specificities stand out with RI index: very low value for CED, higher values for CExD. How to explain the relation $RI(ECEC) < RI(CExD)$? Is this hierarchy due to the quality (transformity) of natural processes involved in the “production” of renewable/non-renewable resources? Looking at these RI results, transformities of non-renewables seem to be more important than renewables (more ecological effort for the non-renewables) declining the RI.

Figure 4 shows the repartition of different resources in CExD and ECEC.

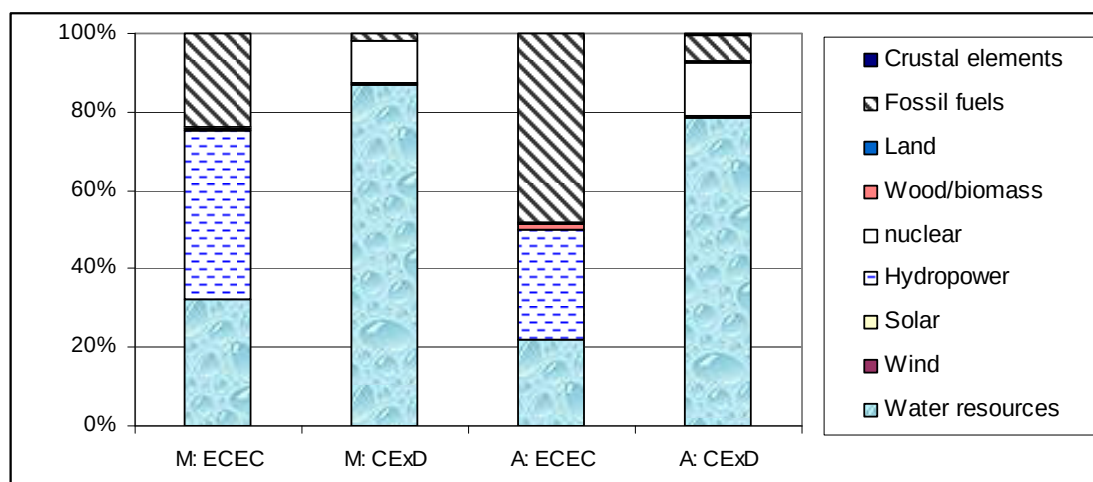


Figure 4. Distribution of resources in CExD and ECEC indicators for sites A and M.

Finally, all R indicators for site A are more important than for site M, meaning that site A is more intensive for all resource consumption. If looking at ECEC for water resources, for producing the same product (1m³ potable water), nature spent twice more effort for water resources used in site A.

The high values of RI(CExD), for both A and M, show that the most useful work (exergy) is extracted from renewable resources (water).

5. CONCLUSION AND OUTLOOK

In this work a practical (draft) method was presented for implementing ecological aspects into LCA tools and results. A form of energy consumption expressed as Ecological Cumulated Exergy Consumption was integrated with the Ecoinvent database.

At a conceptual level, we interrogate about the usefulness and significance of different evaluation methods. Representing resources in terms of energy forms, CED and CExD provide information about short-term, while ECEC considers longer-term issues and the contribution from ecosystems. If the question of representing the non-renewable resources concerns rather their definitive disappearance, the problem is more complicated in the case of renewable ones. How to consider the renewability? How to consider the return of the used streams in the environment? “use” versus “consumption”? These open questions will be addressed further in a PhD work.

ACKNOWLEDGEMENTS

This work is part of the research project EVALEAU funded by French National Agency for Research (ANR), CRP Henri Tudor Luxembourg, INSA Toulouse, Suez Environnement and INRA France.

REFERENCES

- Bösch E., Hellweg S., Huijbregts M. and Fricknecht R. “Applying Cumulative Exergy Demand (CExD) Indicators to the ecoinvent Database”. *International Journal of LCA* 12 (3): 181-190 (2006).
- Buenfil A.A. *Emergy evaluation of water*. A dissertation presented to the graduate school of the University of Florida in partial fulfilment of the requirement for the degree of doctor of philosophy. University of Florida (2001).

- Cohen M.J., Sweeney S. and Brown M.T. "Computing the Unit Emergy Value of Crustal elements. Emergy synthesis 4: theory and application of the emergy methodology". *Proceeding from the fourth biennial emergy conference, Gainesville, Florida (2007)*.
- Costanza R., d'Agre R., de Groot R., Farber S., Grasso M., Hannon B., et al "The value of the world's ecosystem services and natural capital" *Nature*, 1997, 387, 253–260.
- Curie F., Gaillard S., Ducharne A., Bendjoudi H. "Geomorphical methods to characterise wetlands at the scale of the Seine watershed". *Science of the Total Environment* 375, 59-68 (2007).
- Hau J.L. *Integrating Life cycle Assessment, exergy and emergy analyses*. A thesis presented in partial fulfillment of the requirements for degree of Master of Science in the Graduate school of the Ohio State University (2002).
- Millennium Ecosystem Assessment*; www.millenniumassessment.org; accessed April 10, 2010
- Odum H.T. *Environmental Accounting: Emergy and Environmental Decision Making*. Wiley, New York (1996).
- Odum H.T., Brown M.T. and Brandt-Williams S. *Folio #1. Introduction and global budget. Handbook of Emergy evaluation, a compendium of data for emergy computation issued in a series of folios*. University of Florida, Gainesville (2000).
- Odum H.T. *Folio #2. Emergy of global processes. Handbook of emergy evaluation. A compendium of data for emergy computation issued in a series of folios*. University of Florida, Gainesville (2000).
- Yi Z., Singh S., Bakshi B.R. "Accounting for ecosystem services in Life Cycle Assessment, part I: A Critical Review", *Environ. Sci. Technol.* 44, 2010a, 2232–2242
- Yi Z., Singh S., Bakshi B.R. "Accounting for ecosystem services in Life Cycle Assessment, part II: towards and ecologically based LCA". *Environ. Sci. Technol.* 2010b, 44, 2624–2631.

MULTI-OBJECTIVE OPTIMIZATION FOR REMOTE AUTONOMOUS ENERGY SYSTEMS

*Rita Paleta**

Instituto Superior Técnico – Technical University of Lisbon

1. INTRODUCTION

Throughout the world, but mostly in developing countries, there are presently regions where energy supply is inexistent or unreliable, which can compromise socio-economic progress in those places. Authors like J. Rifkin, who supports an upcoming Third Industrial Revolution based on energy progress, affirms that the lack of access to electricity is a key factor in perpetuating poverty around the world. This idea is also shared by many other authors or even by international organizations that claim that the access to electricity is critical for socioeconomic growth. Some of the most important global financing structures like the World Bank (WB), the International Monetary Fund or the International Finance Corporation, are nowadays giving priority to improve energy infrastructures in developing countries, where many poor people suffer from a lack of access to modern energy: nearly 75% of Sub-Saharan Africans (550 million people) do not have access to electricity and in South Asia this numbers rise to 700 million people (representing 50% of the country population), 90% of which live in rural areas. As a result, the WB is planning to expand its support for renewable energy and energy efficiency with special attention to those world areas.

Apart from the lack of infrastructures, there is another crucial issue when analyzing energy systems in developing countries: the kind of energy needs/uses, which are completely different from what is observed in the developed regions like Europe or North America. According with the International Energy Agency (IEA), the households in many non-OECD countries still rely heavily on traditional, non-marketed energy sources, including wood and waste, for heating and cooking. Much of Africa remains unconnected to power grids, and the IEA estimates that the majority of households in sub-Saharan Africa - still rely on fuel wood and charcoal for cooking. This includes for example more than 95% of rural households in Angola villages, which is the focus of the present work. Designing the energy systems of developing countries presents therefore a great challenge: designing a remote autonomous energy system (RAES) that is environmentally and economically sustainable from scratch and that enables social and economic development for the populations.

2. PRELIMINARY RESULTS

In this work it was performed a multi-objective analysis on several different possible configurations in order to choose the most suitable design for a RAES on a particular village in rural Angola.

Firstly, it was used the scarce existing information on electricity consumption to build a feasible load profile - these kind of villages have very low demand profiles once there is only electricity available in public buildings such as the health centre and the building used both as a school during the day and a community centre during the evening. The technological assessment indicated that only PV panels, batteries and diesel generators could be used to produce electricity. Then, the technical and economical performance of

* Presenting author: Rita Paleta e-mail: rita.paleta@ist.utl.pt

the different configurations – PV and batteries or a mix between PV, diesel generator and batteries was obtained using HOMER® simulation software. These multiple solutions were then used to perform a multi-objective analysis in order to aid the decision upon the best configuration. This study considered as optimization objectives the minimization of the levelized cost of electricity (LCOE) [€/kWh], the minimization of the ratio between annual excess electricity production and total annual electricity production (wasted electricity ratio) [%] and the maximization of the renewable electricity production fraction [%]. The analysis shows that to achieve high renewable production ratio, it is necessary to increase significantly the installed renewable capacity to produce energy during the day and store it to be used in the night period, which leads both to higher electricity costs and higher electricity surplus. Thus, the solution that minimizes costs and excess electricity production but still has a high degree of renewable penetration is an hybrid configuration.

This hourly mismatch between renewable electricity production and demand indicates that the improvement of RAES design has to consider a demand management approach - in this case transfer, if possible, part of the night activities that require electricity to the daylight hours.

3. FUTURE WORK

The next steps include the analysis of other energy loads. Regarding specifically the multi-objective analysis method it is also important to consider the initial investment cost, which is a determinant variable when analyzing this kind of project. From the sustainability viewpoint it is not enough to have in mind the renewable production: an objective like yearly CO₂ emissions may also be taken into account.

Keywords: Energy Systems Modeling and Planning, Multi-objective Optimization, Sustainable development

CRITICAL ISSUES IN THE SPATIAL ORGANISATION IN THE TRANSITION TO A SUSTAINABLE ENERGY SYSTEM

Petra Wächter^{*1}, Michael Ornetzeder¹, Anna Schreuer²

*¹Institute of Technology Assessment of the Austrian Academy of Sciences,
Vienna, Austria*

*²Inter-University Research Centre for Technology, Work and Culture, Graz,
Austria*

ABSTRACT

Renewable energy sources have their limitations in available space and are in competition with other uses of the scarce factor land. However, the spatial boundaries are not the only reason making the use of renewable energy resources to a crucial point. The interconnectedness of spatial planning decisions, roadmaps concerning the disposability of renewables and traffic related problems underlines the importance of linking space and energy. The significant increase in average living space per person and the ongoing urban sprawl all have severe implications with regard to energy consumption. Deficits in the implementation of spatial development plans and the distribution of relevant competences on the national, regional and local level often lead to unplanned settlement in the open country and therefore to an increasing demand for energy intensive resources.

In this paper, the results of an ongoing project focusing on the critical issues in the field of energy use and spatial planning in Austria will be presented. Starting from an extended review of the relevant literature in the field and from expert interviews, a backcasting workshop was organized to deepen the understanding and to find possible transition paths towards a more sustainable energy system until 2050. Dealing with such a transition means to be aware of the complex processes of social learning involving a multitude of actors and levels. The emphasis lies also on the discussion of new socio-economic framework conditions and its institutions in spatial planning and regional development.

To overcome the situation of unfavourable planning decisions on a local level, the implementation of subsidies for local amenities gives the chance to encourage local authorities as well as consumers to plan and make use of less energy intensive structures. A foresight-oriented spatial planning providing the facilities of basic needs including work places, schools, shops, medical care, etc. and with a reasonable connection to public transport will avoid urban sprawl and the related traffic volume.

On a more regional level, the enforcement of development axes can provide chances for sustainable development by strengthening and expanding existing infrastructures. The availability of renewable energy resources and public (line bound) modes of transport in an area should be one of the main decision criteria where these axes are developed. High density housing concepts in combination with the supply of public transport can be optimised according to the specific regional situation.

Combining the knowledge of extensive energy use with available energy resources in spatial planning decisions is a main challenge towards a long term sustainable energy system.

Keywords: energy transition, spatial planning decisions, development axes

1. INTRODUCTION

In many areas of society, developments resulting in an increasing energy use can be observed. Planning decisions, transport patterns and extensive domestic energy use are just a few areas where developments in the past were leading to a massive increase

^{*} Corresponding author: Tel.: +43 1 51581 6592; E-mail address: petra.waechter@oeaw.ac.at

in the use of fossil fuels. Environmentally favourable decisions were more the exception than the rule and some development paths with detrimental environmental effects were originally not even seen as environmentally relevant. The past has shown that even the awareness of exhaustible fossil fuels, their impacts on the environment and not even economical burdens because of high energy prices could induce a deep change in the energy system towards sustainability although the rising awareness of society for energy induced environmental problems lead to a plurality of initiatives and actions to change the energy system.

Especially in planning decisions the impact of spatial organisation on the environment is a crucial topic. Spatial organisation patterns address a multitude of environmental, organisational and social dimensions. As part of the energy system, they should be explicitly addressed when talking about an energy transition towards more sustainability. Spatial organisation and planning influence the energy system by the assimilation of renewable energy sources and energy consumption (Stremke and Koh, 2010). Still, it is an unexplored question, how and to what extent spatial organisation can influence a sustainable energy transition.

Decisions in spatial planning are in a lot of cases not driven by the goal of sustainability. Although efforts are made by planning institutions to push sustainable developments the rules are not binding enough to fulfil sustainability criteria at all levels of decision-making authorities. There exist only few examples such as the municipality of Güssing (Austria) which try to accomplish energy-conscious planning on a larger scale.

Spatial organisation heavily depends on the national legislative constitution and therefore it is subject to analysis on a national level to consider the country-specific spatial planning and spatial organisation. Since energy and space are undoubtedly interconnected the investigation of its major subjects such as transport, disposability of renewable energy or energy supply and demand should take place on a regional and local level. Since we cannot regard a simple substitution of energy sources as a sustainable energy transition we have to be aware of the complex structures of a whole energy system.

The paper aims to highlight the preliminary results of the ongoing project E-Trans 2050². Based on the evaluation three strategic key action fields on a sustainable energy transition were identified: the spatial organisation of energy production and use, governance strategies dealing with complexity and uncertainty and the role of the civil society in the transformation of the energy system. This paper will identify critical issues within spatial planning and regional development. The identified topics and their further analysis strengthen the importance of incorporating energy issues at an early stage of planning to avoid the mistakes from the past.

Section 2 gives an overview of critical aspects in spatial planning and organisation concerning energy issues in an international and specifically an Austrian context and its implications. Section 3 deals with backcasting and the experience made in a workshop which was held to deepen the understanding of energy issues in spatial planning whereas Section 4 discusses the results and explores further the critical issues identified within the workshop. The conclusions in Section 5 want to strengthen the need for action and end with a discussion of further research topics.

2. ENERGY ISSUES IN SPATIAL PLANNING AND ORGANISATION

In recent years, the interconnectedness of space and energy gained importance in the discussion in a mainly regional and local context. With the call for more independency from fossil fuel, regional energy systems are the focus of interest in many energy related studies (Graymore et al., 2008; Walz et al., 2007; Madlener et al., 2007; Bohunovsky et al., 2007). Only recently the notion of sustainable landscapes has been established in the discussion of energy and space (Blaschke, 2006).

² The project is funded by the Austrian Climate and Energy Fund.

From a perspective of regional planning and organisation, one of the main topics concerning energy is research on available land needed for the supply and production of renewable energy sources. In Austria, a lot of studies on the potential of hydropower, biomass, wind and solar power exist, but hardly any research was done on the feasibility of using them altogether as supplementary and to treat them as part of a more sustainable energy system – which is definitely more than just using individual renewable energy sources. The Austrian Conference on Spatial Planning (Österreichische Raumordnungskonferenz ÖROK) conducted a study about available land resources for energy production (ÖROK, 2009). Their findings suggest a need for more detailed information for better planning purposes and a need for more comprehensive cooperation with spatial planning agencies and also between the communities. The development of scenarios concerning regional spatial development in Austria (ÖROK, 2008) addresses energy issues only in the way of low mobility costs. Analysis was done about land use in Austria in general, which concludes that land use demands are increasing most strongly in the area of settlement and transport (ÖROK, 2008; Federal Environment Agency, 2010).

In Austria, the increase of land use for settlement is the result of a rise in the demand for single and two families' occupancies. Also in other countries it could be observed that the average demand for living space increases (for example Wulff et al., 2004). Moreover, the overall increasing energy consumption is caused by the fact that urban sprawl is rising and a lot of the new occupancies are built in the open country. These developments give evidence of the deficits in the implementation of spatial development plans and lead to a range of energy related problems: immense traffic volume which has nearly doubled in the period 1990-2010 (Federal Environment Agency, 2009), expenses and environmental effects of the accompanying infrastructure (sewage systems, grids, streets increasing demand for water, electricity, heating, etc.). Attempts to measure urban sprawl ends with the conclusion that some measures are more effective in measuring the sprawl in municipal scale (e.g. density and land use competition) whereas others are more useful on a regional scale (e.g. mean patch size) (Frenkel and Ashkenazi, 2008). Caruso et al. (2009), in their study on urban sprawl, use a microeconomic approach and show that the valuation of open-space amenities increases the speed of urban spread and delays the emergence of an agglomerated urban core.

The focus of the ECOCITY-project³ (Gaffron et al., 2005) was the development of compact, space saving settlement structure enabling an environmentally compatible energy system combined with habitat structures that correspond to the overall objectives for sustainability. The adoption of the urban structure of seven model settlements in Europe resulted in the recommendation of community involvement during the planning phase, public spaces with a high value and a great variety of amenities and sustainable transport concepts adapted to the locally different conditions. Further, Fillion (2001) argues that the strategy of combining multifunctional nodes with high density, transit orientated corridors with residential density would be effective for successful intensification in order to reduce the every day use of cars.

In the transport sector, new modes of transport does not mean to decrease the possibility of mobility but long term spatial planning concepts can support solutions to the construction and increased use of public transport. Spatial planning can influence energy consumption caused by transportation not only by reorganising settlement patterns but also through adaptation of existing and development of new transport infrastructure. This includes intelligent transportation systems, city-logistic systems and infrastructure for e-mobility. In Austria decisions in the mobility sector and in spatial planning are not linked in regional and local governance institutions so far, making it even more difficult to implement changes towards more sustainability.

Decisions on land use have economical, social and environmental (including energy related) impacts. Studies that deal with the complexity of sustainable energy systems have mostly a focus on socio-technical transitions rather than on space (Späth and

³ The project ECOCITY was funded within the 5th EU framework programme in the period 2002-2005.

Rohracher, 2010). Therefore, relating quantitative studies about potentials of renewable energy sources with spatial organisation and planning is an underdeveloped field in sustainability research. Since renewable energy sources have their boundaries in the available land it is not possible to make use of them to an unlimited extent. Combined with the re-organisation of existing infrastructure and new transport modes, spatial planning decisions play a major role in transitions towards a sustainable energy system. One aim of the project E-Trans 2050 is to detect the most important energy issues in spatial organisation and to discuss them in the light of a sustainable transition taking account of relevant actors and institutions. Furthermore we want to detect critical issues that may hinder identified favourable developments to a long term energy transition.

3. BACKCASTING IN ENERGY RESEARCH

Within the project E-Trans 2050 a backcasting approach was chosen to investigate issues related to the spatial organisation of the energy system. A backcasting process can be understood as a particular form of scenario process with an explicitly normative angle. It involves the development of one or more scenarios that are considered desirable and a subsequent identification and implementation of strategies that help achieve this future state.

The backcasting approach was put forward in the 1970s and 1980s in energy research and strategy development in Canada and the US. It was deliberately developed and named in contrast to the widely used approach of forecasting. While forecasting generally attempts to provide a prediction the *most likely* future developments, backcasting attempts first to generate particularly *desirable* images of the future and then to search for possible ways of reaching this future state (Robinson, 2003). Backcasting thereby emphasises the societal room for manoeuvre in shaping future developments, e.g. via the implementation of particular policy measures. Thus, in a backcasting process it is not uncommon to develop scenarios that deliberately involve a breaking of current trends (Robinson, 2003). According to Dreborg (1996) backcasting therefore is regarded particularly useful when problems are complex, when there is a need for far-reaching change, when dominant trends are part of the problem situation and when the planning horizon is sufficiently long to open up sufficient room for manoeuvre.

From the 1980s onwards, backcasting has also been applied in other fields related to sustainable development, such as mobility, nutrition and sustainable land use (Quist and Vergragt, 2006; Quist, 2007). Apart from that backcasting processes increasingly make use of participatory approaches („participative backcasting“) enabling the involvement of a variety of societal actors (Quist and Vergragt, 2006; Robinson, 2003). Furthermore backcasting is meanwhile also used for strategy development at the level of individual regions or even companies. Thus the aspect of strategy development does not necessarily have to focus on the development of policy measures (Quist and Vergragt, 2006).

Backcasting processes can differ in their specific form of implementation but usually consist of the following steps (see Quist and Vergragt, 2006 p. 1033 and Quist, 2007 p. 24-29):

- (1) Strategic problem orientation (analysis of current situation, specification of goals and assessment criteria, consideration of external factors, etc.)
- (2) Development and assessment of scenario(s)
- (3) Strategy development to achieve desirable scenario(s)
- (4) Selection and elaboration of measures to be adopted
- (5) Implementation and follow-up

In many cases the strategy development step is also referred to as ‘backcasting’ in itself, even though the same term is used to describe the overall process.

Within the project ‘E-Trans 2050’ the first two steps were achieved via a literature review as well as via two expert workshops dedicated to scenario development. This

resulted in a ‘sustainability scenario’ for the Austrian energy system in 2050 which was further refined with respect to issues of spatial organisation based on eight expert interviews and a literature review (see Table 1). An additional expert workshop was devoted to strategy development for achieving these sustainability goals in the area of the spatial organisation in the energy system.

4. STRATEGIES DISCUSSED IN THE BACKCASTING WORKSHOP

Taking the proposed long term vision (Table 1) as a commonly accepted starting point participants of the expert-workshop were invited to discuss strategies and necessary milestones that could be helpful to reach this future vision. On a more general level the discussion in the workshop again made clear that changes in the spatial organisation regarding the production and consumption of energy depend on a multitude of interconnected factors. Among other aspects, the discussion revolved around technological innovation, administrative and legal reforms, binding political targets, greening of the tax system, demonstration projects, regional networks, international trends, etc. Even so, focussing on specific aspects of the overall topic the participants were able to formulate a number of recommendations concerning both main aspects of the topic (settlement structures, mobility and infrastructure) as well as specificities such as the development of large-scale demonstration projects.

Table 1. Long term vision energy and spatial organisation

Long term vision 2050		
Main aspects	Prepared vision	Comments from workshop participants
General data	- Population in Austria: 9.5 m (2010: 8.4 m) - Gross domestic energy consumption: 800 PJ (approx. 50% less compared to 2010) - Electricity consumption has increased compared to 2010 by about 20% - Renewable energy sources cover 90% of domestic needs - CO₂ emissions are 80% below the 1990 level	- Consider the special role of Austria regarding e-mobility (could be afforded by high percentage of hydro power) - Consider nuclear energy, hydrogen - Consider energy trading - Electricity consumption has to decrease - Consider political and legal conditions
Energy prices	- All forms of energy are much more expensive than 2010 - Fossil fuels are about twice as expensive as renewable forms of energy - Percentage of household expenditure on energy as in 2010 (around 7%) - Social distortion be prevented through the tax system and transfer payments	- Consider learning curve regarding renewables, some forms of energy could be cheaper in 2050
Infrastructure	- Energy is used extremely efficiently in all areas - Power grid is completely modernized (new and efficient equipment, smart grids, super grids) - Highly-efficiency devices are the norm - About 50% of the building stock corresponds to passive house standard, the rest is below low-energy standard	- Super grids are not desirable - Energy standards in 2050 very ambitious - Ownership structures are important - Also consider regional energy storage, for example compressed air storage, etc. - Consider construction of new power plants
Spatial dimensions of production and use	- Widespread use of renewable forms of energy - Use of renewables adapted optimally to local and regional conditions - Previously existing capacities are upgraded and slightly expanded - Consumption and production are located in	- Consider rare raw materials - 90% of gross domestic consumption from renewable forms of energy - Proximity of production and consumption required for heating,

	close proximity	not for electricity
	- Widespread use of energy cascading	- Conflicts between food and biomass production
		- Problems from intensified agriculture
Mobility and transport infrastructure	- Energy demand for mobility is below the level of 2010 - More efficient technologies, reduced traffic volume - Improved public transport system - Compact settlement patterns ("short distances") - High proportion of bicycle traffic - Highly efficient logistics solutions for goods transport	- Reduction of mobility is not desirable, more important to reduce mileage - Mobility will not decrease - Is electric mobility sustainable?
Settlement structures	- Urban centres and medium-sized cities are the main areas for living and working - Suburban areas are compact, high quality of life in these neighbourhoods - Peripheral regions are of small economic importance - Rural regions have been diminished in a "socially acceptable" way, elite remainders of settlements, nature reserves	- The big centers should not continue to grow, polycentric development would be of importance - Less urban sprawl is desirable, but depopulated rural areas are not desirable - Links between regional centres and smaller villages are important - What does "diminished in a "socially acceptable way" mean?

A major part of the discussion focussed on the development of sustainable settlement structures. Important goals here are the reduction of energy demand in buildings as well as for mobility needs and to enable the widespread use of renewable forms of energy. New developments should be compact, build according to ultra-low energy standards, connected to district heating systems (if available), be well connected to public transport systems and optimised for using solar energy. Existing settlements are to be transformed step-by-step according these criteria. In order to achieve these goals changes in building regulations, zoning plans and the fiscal transfer regime between the federal government, federal states and municipalities were considered very important. However, most participants of the workshop agreed that the subsidy schemes provided by the federal states are the most important and effective tool to stimulate changes in the building sector in the short run (including a shift from subsidies for new construction to refurbishment and densification measures). These schemes could be changed much easier compared to building standards and similar regulations and given the high impact of subsidies in the building sector expected effects were high. Among others things, stable traditions in the construction sector, powerful visions of "the happy family in the detached house" or the sheer number of construction plans for which permissions have already been issued were identified as major barriers in this field.

Mobility – the second main field of discussion – was regarded as a major precondition for modern society and therefore the goal formulated in advance that the demand for mobility in 2050 should be lower than in 2010 was clearly rejected. Instead it was preferred to aim at a reduction of mobility induced energy consumption. Beside the already discussed changes in the settlement structure the workshop participants focussed on improved public transport systems and the development of e-mobility. The public transport system should be improved in close cooperation with other means of transport to solve the "first and last mile problem" in an environmentally sound way, e.g. by using electric vehicles or electric bicycles. E-mobility was also seen an opportunity to loosen the perception of a close association between individual mobility and car ownership (less private owned cars could help to increase the attractiveness of public transport). Moreover it was stated that public transport systems have to be improved by using information

technology to optimise the interplay of different subsystems and by implementing attractive tariffs and transparent accounting systems.

The development of large-scale demonstration projects was discussed as an additional strategy on the way to an energy efficient spatial organisation. Such projects could be seen as experimentation fields trying to integrate the various requirements and aims as defined in the long-term vision 2050. Learning from such experiments was seen as an important precondition for the further and more widespread dissemination of sustainable solutions. As local and financially limited projects they could be realised on a short-term basis primarily dependent on political will and financial resources but more or less independent from substantial changes in the regulatory system. In order to gain as much impact as possible those projects should either be located in so far sparsely populated suburban areas or in smaller cities acting as regional centres, which both were seen as crucial for future developments.

All in all the discussions in the workshop produced a large number of ideas, especially regarding the transition of settlement structures. However, only some of them – like the development of demonstration projects – could be discussed in more detail. Other ideas will be picked up only in the future and elaborated in the remaining part of the research project.

5. CONCLUSIONS

Especially in decisions regarding spatial organisation, we are confronted with the fact that new forms and rules of organisation take a long period of time until they take effects. The planning horizon usually is about 20-25 years; therefore it is of high importance to implement and to put into practice the knowledge we already have towards a more sustainable spatial organisation.

One of the main conclusions we can draw so far comes from the well discussed critical issue of urban sprawl. Some experts advance a radical view of rebuilding settlements in the open country and recommend to enforce relocation or even demolition by law like it is done in the case of land use by governmental ordinance in order to build new streets (compulsory expropriation) and they also call for a merging of small villages which are most strongly effected by rural depopulation. The current approach of assessing each individual case of a new building in these areas could be replaced by a complete ban on new constructions. Insofar as all far reaching reforms in administration need a change in the constitution it will be difficult to implement. Overcoming the problem of the fragmentation of competences of legal authorities and institutions of spatial planning requires the reduction of competences of local authorities. The actors involved would certainly not favour this top-down driven change and it seems that it is not a feasible option to cut the competences of local and regional decision makers in order to achieve the goal of more sustainable landscapes. Social engagement and bottom-up processes should be rather encouraged and established than even reduced and the legal authorities of spatial planning can be re-organised and new incentive structures for local authorities should be established in order to make ecologically more favourable planning decisions.

Some expert opinions were more moderate, calling for more information on ecological and energy issues in spatial planning for stakeholders involved and executive institutions. The mistakes made in the past (i.e. scattered settlements) should not be removed but instead in the future, the developments should evolve in an indirect way regarding spatial organisation. One policy instrument could be the redefinition of subsidies for the construction of single dwellings. Nowadays costs for the provision of infrastructure services do not depend on the spatial geographical position. However, by including criteria of location in the subsidies a better guidance effect could be achieved. One criterion could be the admission for subsidies only for single occupancies in regional centres and in urban suburbs.

The discussions among the participants of the workshop lead to the conclusion that the mutual expectations of experts and decision-makers in the field of renewable energy

resources and spatial planning and organisation are sometimes too high. Therefore, better cooperation is needed towards a more sustainable energy system.

In terms of spatial planning, a planning period of 40 years is not long. Changes in spatial organisation, even if they are implemented today, would need a time span of at least twenty years in order to produce any effects and allow us to profit from more sustainable regions including energy production and, transport and wise planning decisions. The critical issues pictured reflect the need for action and strengthen the importance of linking energy and space.

REFERENCES

- Blaschke, Thomas (2006): "The role of the spatial dimension within the framework of sustainable landscapes and natural capital". *Landscape and Urban Planning* 75, pp. 198-226
- Bohunovsky, Lisa, Madlener, Reinhard, Omann, Ines, Bruckner, Martin, Stagl, Sigrid (2007): "Die Lokale Energienutzung der Zukunft - Integrierte Nachhaltigkeitsbewertung von lokalen Energieszenarien". *Ökologisches Wirtschaften* 2, pp. 47-50
- Caruso, Geoffrey, Peeters, Dominique, Cavailhe, Jean, Rounsevell, Mark (2009): "Space – time patterns of urban sprawl, a 1D cellular automata and microeconomic approach". *Environment and Planning B* 36, pp. 968-988
- Dreborg, Karl Henrik (1996): "Essence of Backcasting". *Futures* 28, pp. 813-828
- Federal Environment Agency (2010): <http://www.umweltbundesamt.at/umweltschutz/raumordnung/flaechenverbrauch> (accessed 10-09-13)
- Federal Environment Agency (2009): *Umweltbundesamt – Klimaschutzbericht*. Report REP-0226. <http://www.umweltbundesamt.at/fileadmin/site/publikationen/REP0226.pdf> (accessed 10-09-14)
- Filion, Pierre (2001): "Suburban mixed-use centres and urban dispersion: what difference do they make?" *Environment and Planning A* 33, pp. 141-160
- Frenkel, Amnon and Maya Ashkenazi (2008): "Measuring urban sprawl: how can we deal with it?" *Environment and Planning B* 35, pp. 56-79
- Gaffron, Philine, Huismans, Gé, Skala, Franz (2005): *Ecocity – A better place to live*. Book I. Project report.
- Graymore, Michelle, Neil G. Sipe, Roy E. Rickson (2008): "Regional sustainability: How useful are current tools of sustainability assessment at the regional scale?" *Ecological Economics* 67, pp. 362-372
- Madlener, Reinhard, Kowalski, Katharina, Stagl, Sigrid (2007): "New ways of integrated appraisal of national energy scenarios: the case of renewable energy use in Austria". *Energy Policy* 35 (12), pp. 6060-6074
- ÖROK 2008/2009 *Szenarien der Raumentwicklung Österreichs*
- ÖROK 2009 *Energie und Raumentwicklung – Räumliche Potenziale erneuerbarer Energieträger*
- Quist, Jaco and Philip Vergragt (2006): "Past and future of Backcasting: The shift to stakeholder participatin and a proposal for a methodological framework". *Futures* 38, pp. 1027-1045
- Quist, Jaco (2007): *Backcasting for a sustainable future: the impact after 10 years*, Eburon Academic Publishers, Delft
- Robinson, J. (2003): "Future subjunctive: Backcasting as social learning". *Futures* 35, pp. 839-856
- Späth, Philipp and Harald Rohrer (2010): "[Energy regions: The transformative power of regional discourses on socio-technical futures](#)". *Research Policy* 39 (4), pp. 449-458
- Stremke, Sven and Jusuck Koh (2010): "Ecological concepts and strategies with relevance to energy-conscious spatial planning and design". *Environment and Planning B* 37, pp. 518-532
- Walz, Ariane, Corina Lardelli, Heiko Behrendt, Adrienne Grêt-Regamey, Corinne Lundström, Susanne Kytzia, Peter Bebi (2007): "Participatory scenario analysis for integrated regional modelling". *Landscape and Urban Planning* 81, pp. 114-131
- Wulff, Maryann, Ernest Healy, Margaret Reynolds (2004): "Why don't small households live in small dwellings? Disentangling a planning dilemma". *People and Place* 12(1), pp. 57-70

ON BENEFITS AND PERSPECTIVES OF APPLYING NETWORK THEORY TO ENERGY SYSTEMS

Franco Ruzzenenti^{*1,3}, Diego Garlaschelli² and Riccardo Basosi^{1,3}

¹ *Center for the Study of Complex Systems, University of Siena, Via Roma 56, 53100 Siena, Italy*

² *LEM, Sant'Anna School of Advanced Studies, P.zza Martiri della Libertà 33, 56127 Pisa, Italy*

³ *Department of Chemistry, University of Siena, Via Aldo Moro 1, 53100 Siena, Italy*

ABSTRACT

While the *energy issue* is rising in the agenda of politics, the awareness that complexity is a main and distinctive feature of energy systems is becoming dominant in the scientific milieu. There is a trend in nature, from the beginning of life to higher organism, that justifies the hypothesis that evolution tends to promote higher complexity and higher energy density, throughout higher thermodynamic efficiency. An ever growing energy trend that is perpetuated in human made systems, as society and economy development clearly explain. Some scientist claim this is a universal tendency common to any energy systems. Is therefore the higher efficiency-higher complexity-higher energy consumption an inescapable drift? Can economic growth and development exists out of energy growth? Crucial questions of the like pave the way of the current debate over the *energy issue* and cannot be answered without tackling the broader question of complex systems' evolution. Two main approaches over complexity studies are emerging in science: Non-linear Dynamics and Network Theory. Since the birth, more than two centuries ago, of Graph Theory as a mathematical approach to networks, network theory has developed dramatically in the last decades in virtue of an extraordinary amount of data available and computational tools, broad up by information technologies. However, so far, Network Theory has seldom tackled energy systems. In this article we aim at advocating the need for a Network Theory-based theoretical framework, directed at interpreting energy systems. Two main supportive arguments will be advanced and for each argument, thrives and shortcomings will be considered. One argument will concern the methodological aspects descending from the two above mentioned approaches on complexity. It will be illustrated how network theory has the indisputable advantage of considering changes that simultaneously take place in any level or any region of the entire systems. Furthermore, in Network Theory, differently from approaches based on dynamics though non-linear, space has not be assumed invariant. The second argument proposed concerns some practical and more applicative aspects of network theory.

Keywords: Network Theory, Symmetry Breaking, Complexity, Energy Efficiency, Energy Growth

1. INTRODUCTION

More then twenty years ago, Marshall McLuhan, in the field of communication theory, advocated the need to overcome the constrains of conventional theories about communication, according to him relegated to an Euclidean and 'visual' space, to achieve a new theory based on an ubiquitous and synchronous space, in his words: an 'acoustic space'. He advanced the point that space (and not just time) is an agent of communication. According to him, printed texts have educated us to a sequential type of communication, whereas the electronic age developed spatial communication: actors communicate in the same time with the environment and mutually between them

* Corresponding author; E-mail: ruzzenenti@unisi.it

[Richard(2009)]. Nevertheless, in his opinion, communication theory did not follow changes in communication media. In his own words: 'The basis of all contemporary Western theories of communication - the Shannon-Weaver model - is a characteristic example of left-hemisphere lineal bias. It ignores the surrounding environment as a kind of pipeline model of a hardware container for software content. It stresses the idea of inside and outside and assumes that communication is a literal matching rather than making' [McLuhan and Powers(1989)].

The problem of describing Complex Systems by a paradigm *lineal biased*, meaning that interactions among parts are considered separately and sequentially, as it would appear in a diachronic instead of synchronic space, is that not always it is possible to reduce a global change to a local dynamics. This is very clear if we consider, for example, a phase transition: in the surrounding of the critical value each single particle doesn't exhibit any information about its future state, never the less, at criticality every particle behaves collectively. The change is sudden and unpredictable by looking at particles interactions, as it comes from *the space* and it affects the system. We believe a similar phenomenon is ubiquitous to Complex Systems' development and consistently approaches to the study of Complexity should draw inspiration from the study phase of transition. Besides, a well-founded approach of the sort, should be holistic at the most.

In the light of what has been exposed above, we would like now to advocate the use Network Theory as an effective and insightful method to deal with complex systems. Network Theory is intrinsically 'spatial' and 'global', and it best suits the need for a holistic theory versus a sequential theory. Most complex systems encountered in a diverse range of domains, from biology through sociology to technology, consist of networks of elements (*vertices*) connected together (by *links*, or *edges*) in an intricate way [Caldarelli(2007)]. While graph theory started dealing with the mathematical description of network properties long ago [Harary(1994)], only recently massive datasets about large real-world complex networks have become available. This allowed an unprecedented activity of data analysis, which resulted in the establishment of some key 'stylized facts' about the structure of real networks, and motivated an intense theoretical activity aimed at explaining them.

Surprisingly (at least at the time when this was first observed), the empirically observed structure of real networks is strikingly different from what is obtained assuming simple homogeneous mechanisms of network formation, such as the traditional Erdős-Rényi random graph model [Caldarelli(2007)]. In the latter every pair of vertices has the same probability p to be connected. This generates homogeneous topological features, such as a constant link density across the network, and a narrow (binomial) distribution of the degree k (number of edges reaching a vertex). By contrast, virtually any real network is found to display a modular structure, with vertices organized in communities tightly connected internally and loosely connected to each other, and a broad degree distribution, typically featuring a power-law tail of the form $P(k) \propto k^{-\gamma}$. Networks characterized by the latter property are called *scale-free*. Besides the purely topological level, networks are also characterized by heterogeneous link weights. That is, the intensity of the connections is again broadly distributed, and non-trivially correlated to the topology. At both the topological and the weighted level, many real networks are also characterized by an intrinsic directionality of their connections, which again implies that proper quantities must be introduced and measured in order to fully understand directed structural patterns [Garlaschelli and Loffredo(2004a), Garlaschelli and Loffredo(2006), Fagiolo(2007)]. As an additional level of complexity, dynamical processes generally take place on networks [Barrat et al.(2008) Barrat, Barthelemy, and Vespignani]. Remarkably, the heterogeneous structure of real networks has been found to determine major deviations from the behavior expected in the homogeneous case, which is the traditional assumption used to obtain predictions about the dynamics. As a consequence, most of these predictions have been shown to be incorrect when applied to real-world networks. A prototypic example of this discrepancy is found in models of epidemic disease spreading. When these models are defined on regular graphs, one finds that the transmission rate must overcome a finite *epidemic threshold* in order to guarantee the persistence of an infection. By contrast, on

scale-free networks the value of the epidemic threshold vanishes, implying that a large class of diseases can escape extinction no matter their transmission rates, even if extremely low [Barrat et al.(2008) Barrat, Barthelemy, and Vespignani]. Finally, in some networks a feedback is present between the topology and the dynamics taking place on it. This is the case of adaptive networks, whose structure changes in response to their dynamical behavior, which is in turn affected by the structure itself [Gross and Sayama(2009)]. Generally, adaptive networks cannot be properly understood by studying their topology and their dynamics separately, as simple models show [Garlaschelli et al.(2007a)Garlaschelli, Capocci, and Caldarelli].

2. THEORETICAL FRAMEWORK

2.1 Symmetry in networks

'All scientific applications of symmetry are based on the principle that *identical causes produce identical effects*' [Rosen(1975)]. That is to say, the symmetry of the effect must be at least that of the cause, or in a mathematical jargon: the order of the *symmetry group* of the effect must be at least equivalent to that of the cause. Nevertheless, for a qualitatively new phenomenon to occur, symmetry cannot be conserved. Pierre Curie was the first in modern science who highlighted the relevance of spontaneous symmetry breaking in various phenomena [Lin(2001)]. His studies of criticality in phase transitions overcame the boundaries of solid state physics and posed a suitable analytical framework for further studies, in different fields. Prigogine himself, a renowned and illustrious precursor of complex systems research, referred to Curie's contribution in order to elucidate the meaning of symmetry breaking in dissipative structures: 'We see therefore, that the appearance of a periodic reaction is a time-symmetry breaking process exactly as ferromagnetism is a space-symmetry breaking one' [Prigogine(1977)]. Two main viewpoints on symmetry breaking developed in science: one concerned with space symmetry and one with time symmetry. Symmetry breaking can be indeed approached from two different sides: from a time-scale perspective, as we see the phenomenon as a dynamic system, or from a spatial perspective, as we focus on changes in the system's space. With the former approach we tend to consider changes that are endogenous to the system, while space is taken as homogeneous all the way through; with the latter, the system is embedded in some space and changes are considered exogenous. However, whereas in physics space-symmetry breaking has been a prominent research subject, in the field of complex nonlinear systems time-symmetry breaking has received much more attention. The following passage by Mainzer illustrates on what basis time symmetry breaking became a major topic in the science of complexity: 'Thus, bifurcation mathematically only means the emergence of new solutions of equations at critical values. Actually, bifurcation and symmetry breaking is a purely mathematical consequence of the theory of nonlinear differential equations. But, bifurcations of final states as solutions of differential equations correspond to qualitative changes of dynamical systems and the emergence of new phenomena in nature and society [...]'[Mainzer(2005)].

Therefore, how far can we go exploring the statistical mechanics metaphor given that complex networks are not solid state matter? That is to say: to what extent concepts like *symmetry* and *space* can be applied to networks? We would like to highlight that some graphs may be embedded in a metric space where vertices are assigned positions. In this case, the symmetries (automorphisms) of a graph are induced by the transformations of coordinates in the embedding space, even if topologically they are simply permutations of vertices. This means that the topological properties of the graph, which are independent of the embedding space, will nonetheless reflect the properties of the latter [Ruzzenenti et al.()Ruzzenenti, Garlaschelli, and Basosi]. For instance, lattices are naturally formed by connecting vertices to their nearest neighbours in some embedding space. A simple type of discrete symmetry encountered in (either infinite or periodic) regular lattices is translational symmetry. That is, the fact that the topology of a

lattice embedded in some D -dimensional space does not change after a displacement by an integer multiple of the lattice spacing. Lattices are a particular type of *regular graphs*,

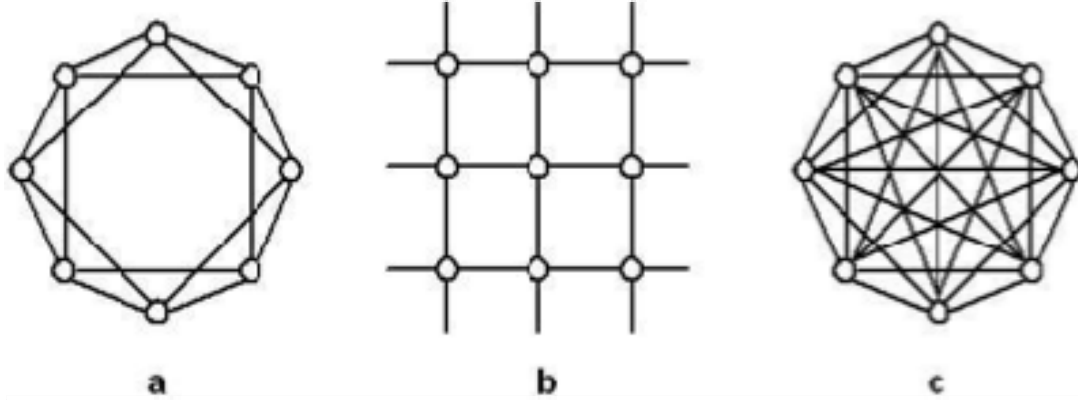


Figure 1. Examples of regular graphs. **a)** A periodic one-dimensional ($D = 1$) lattice (i.e. a ring) where each vertex is connected to its nearest and second-nearest neighbours. **b)** A two-dimensional ($D = 2$) lattice (in principle of infinite size) where each vertex is connected only to its nearest neighbours. **c)** A complete graph where every vertex is connected to all other vertices. A complete graph can be regarded either as a lattice embedded in some space of finite dimension $D < \infty$ (as in the two previous examples) with infinite-ranged connections, or as a lattice embedded in infinite dimension $D = \infty$ with finite-ranged (as in the two previous examples) connections.

i.e. graphs where every vertex has the same number of neighbours. In fig.1 we show three examples of regular graphs embedded in different dimensions ($D = 1$, $D = 2$ and $D = \infty$) and with differently ranged connections (nearest neighbours, nearest and second-nearest neighbours, infinite neighbours). If the labeling of vertices reflects their position in space, then translational symmetry is reflected in some regularities of the adjacency matrix A of the network (for undirected graphs, where no orientation is defined on the edges, the adjacency matrix A is a binary matrix whose entries equal $a_{ij} = 1$ if a link between vertex i and vertex j is present, and $a_{ij} = 0$ otherwise; here $i = 1, \dots, N$ where N is the total number of vertices, i.e. the size of the network). For instance, if the vertices are numbered cyclically along the ring, the adjacency matrices A_a and A_c of the graphs shown in fig.1a and fig.1c read

$$A_a = \begin{pmatrix} 0 & 1 & 1 & 0 & 0 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \end{pmatrix} \quad A_c = \begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{pmatrix} \quad (1)$$

respectively. Translational symmetry is one of the traditional assumptions used in the theoretical study of discrete (or discretized) dynamical systems, and most of the available analytical results about dynamical processes are only valid under the assumption of the existence of this symmetry.

However, as one moves beyond the simple case of atoms regularly embedded in crystal lattices, virtually all real-world networks strongly violate translational symmetry. An important deviation from lattice-like topology in real networks is signaled by a surprisingly small value of the average *inter-vertex distance*, i.e. the average number of links one needs to traverse along the shortest path connecting two vertices. In most real networks, this quantity increases at most logarithmically with the number N of vertices, a phenomenon known as the *small-world* effect [Caldarelli(2007)]. This behavior is also encountered in the random graph model but not in lattices, where the average distance (if

infinite-ranged connections are not allowed, e.g. for the graphs in fig.1a and fig.1b but not for that in fig.1c) grows as $N^{1/D}$, thus much faster. The breakdown of translational symmetry implies that the wealth of knowledge accumulated in the literature about the outcome of dynamical processes on lattices cannot be applied to the same processes when they take place on real networks [Barrat et al.(2008)Barrat, Barthelemy, and Vespignani]. We already mentioned epidemic spreading processes as an example of the surprising deviation between dynamics on lattices and on more complicated networks.

2.2 Symmetry breaking: source of changes

What we should bear in mind, when we consider symmetry breaking in the field of network theory, is that symmetry (invariance) is hard to depict unless we use analytical tools. Our imagination, intended as the faculty of forming images, has been educated to depict shapes in Euclidean spaces. Whenever we must traduce shapes from Euclidean to topological spaces, we are inevitably biased by the fact the we tend to recall the Euclidean representation of forms in the new space. This overlapping of spaces generates misrepresentation. To better stress out the conundrum of spaces' inequality representation, in fig.2 we picture the trade network of Europe (EU-15), as it would appear in topological space (left panel) and in Euclidean space (middle panel), assuming that trades travel mainly on the road network. While the Euclidean representation of the road network, except for the scale and a certain degree of abstraction, is conformal to the real system's shape, the corresponding representation of the trade network in a metric space (the plane), is purely conventional. Indeed, we could have represented the same network in several different ways, e.g. arraying in a circle or randomly scattering nodes. We could actually produce *ad libitum* different Euclidean embeddings of the same graph. The topological-Euclidean dichotomy is further complicated by the fact the system represented by the trade network is immersed in an economic space, involving variables and relations in large number, that are not detected in the network. Consider for example the traveling time of goods, which is determined by several exogenous factors. Traveling time, together with energy efficiency and labor costs, is among the major factors affecting shipping costs. In the right panel of fig.2 we show a 'metric representation' of the space modification due to traveling time [Spiekermann and Wegener(1996)]. It is noteworthy that in an economic space distances are not merely Euclidean and the compound metric is made by length, time, labor costs and energy units at the minimum.

Symmetry breaking may occur in a different space, that is only indirectly represented in the topological space. This indirect consequence complicates a clear understanding of the underlying process, but future research must explore this scenario more thoroughly and possibly shed light on the relation between network dynamics, symmetry breaking, the causal chain and its premises. Indeed, the intriguing result that the World Trade Web (WTW in what follows) is excellently reproduced by a connection probability that uniquely depends on the GDP of countries [Garlaschelli and Loffredo(2004b), Garlaschelli and Loffredo(2005)] suggests various interesting considerations. In regular lattices the overall permutation symmetry of vertices is broken by positions in Euclidean space and is restricted to invariances of lesser order such as translational symmetry. In geographically embedded networks such as that shown in the middle panel of fig.2, the irregularity of the geography further restricts the symmetry properties. When additional variables are also taken into account, even stronger distortions take place as in the right panel of fig.2, and in the case of the WTW we are in an extreme situation where the symmetry-breaking variable is virtually only the GDP, and the distance dependence practically disappears. The properties of the network must be therefore interpreted in economic space rather than geographic space. Still, in this space we find a remarkable symmetry: countries with the same GDP are statistically equivalent, and pairs of countries with the same couple of GDP values have the same probability to trade. In other words, we can rephrase the symmetry properties of the WTW in terms of

the GDP values rather than the degree sequence. This invariance is preserved despite the heterogeneity of the GDP across world countries increases in time [Garlaschelli et al



Figure 2. European (EU-15) trade network as it would appear in topological space (left panel), in Euclidean space assuming that trades travel mainly on the road network (middle panel, from http://en.wikipedia.org/wiki/Image:International_E_Road_Network.png), and after also taking into account the space modification due to traveling times (right panel, after [Spiekermann and Wegener(1996)]).

(2007b) Garlaschelli, Di Matteo, Aste, Caldarelli, and Loffredo which means that the intensity of the GDP-induced symmetry breaking also increases. And, despite the latter determines ever-increasing divergences between the values of the connection probability q_{ij} across pairs of countries, the average probability $2 \sum_{i < j} q_{ij} / N(N-1)$ remains almost constant as indicated by the stationarity of the undirected connectance².

3. APPLICATIONS

3.1 Symmetry breaking in the WTW

Reciprocity is the tendency of pairs of vertices to be connected by two mutual links pointing in opposite directions, a particular type of correlation found in directed networks [Garlaschelli and Loffredo(2004a), Garlaschelli and Loffredo(2006)]. Depending on the nature of the network, reciprocity is related to various important phenomena, such as ecological symbiosis in food webs, reversibility of biochemical reactions in metabolic networks, bidirectionality of chemical synapses in neural networks, synonymy in networks of dictionary terms, mutuality of psychological associations in networks of freely linked words, reciprocity of hyperlinks in the WWW, crossed financial ownership in shareholding networks, economic interdependence of countries in the international trade network, and so on [Garlaschelli and Loffredo(2004a)]. Therefore, while the total number of directed links is given by

$$L = \sum_{i,j} a_{ij} \quad (2)$$

the number of reciprocated links is

² The link density, or connectance, of the undirected network is the ratio between L^u and the maximum

number of undirected links, i.e. $\frac{L^u}{N(N-1)/2} = \frac{2}{N(N-1)} \sum_{i,j} a_{ij}$ [Garlaschelli and Loffredo(2004a)]

$$L^{\leftrightarrow} = \sum_{i,j} a_{ij} a_{ji} \quad (3)$$

Since $0 \leq L^{\leftrightarrow} \leq L$, the traditional definition of the reciprocity of a network is

$$r = \frac{L^{\leftrightarrow}}{L} \quad (4)$$

Since $0 \leq L^{\leftrightarrow} \leq L$, the traditional definition of the reciprocity of a network is so that $0 \leq r \leq 1$. Although not usually remarked, it is important to notice that whether the value of r can actually span the entire range between 0 and 1 depends on the link density (or *connectance*) of the network, defined as

$$d = \frac{\sum_{i,j} a_{ij}}{N(N-1)} = \frac{L}{N(N-1)} \quad (5)$$

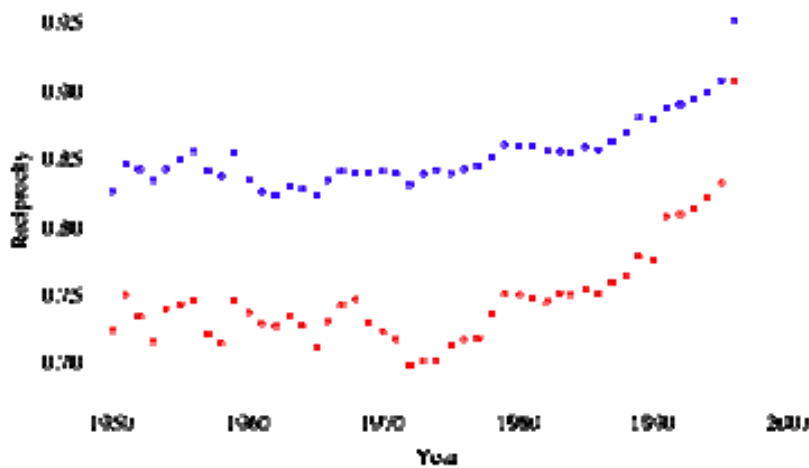


Figure 3. Evolution of the reciprocity measures $r(t)$ (blue points) and $\rho(t)$ (red points) in the directed version of the World Trade Web.

In order to overcome this problem, a new definition of reciprocity was proposed [Garlaschelli and Loffredo(2004a)] as the Pearson correlation coefficient between the symmetric entries of the adjacency matrix:

$$\rho = \frac{\sum_{i,j} (a_{ij} - d_i)(a_{ji} - d_j)}{\sqrt{\sum_{i,j} (a_{ij} - d_i)^2 \sum_{i,j} (a_{ji} - d_j)^2}} = \frac{r - d}{1 - d} \quad (6)$$

Indeed, the second ingredient -besides the degree sequence or the GDP- required in order to explain the topological properties of the WTW is the reciprocity r , which coincides with the conditional connection probability r_0 . While the marginal connection probability varies greatly among different pairs of vertices, a property that can be traced back to the heterogeneous degrees and possibly explained by the GDP values, the conditional connection probability is uniform and must therefore be related to a completely different mechanism. The heterogeneity of vertex degrees, or of GDP values, is completely reflected in the marginal connection probability while it is not reflected at all in the conditional connection probability and in the reciprocity. To better understand the

problem, we now consider the temporal evolution of the reciprocity and show how this may suggest possible explanations.

In particular, we see that $r(t)$ has been fluctuating about a constant value from 1950 to the late 1970's. Then, from the late 1970's to the late 1990's, a steady increase of $r(t)$ took place. More importantly, this occurred despite the density of undirected trade relationships (the undirected connectance b^- remained approximately constant during the same period. This indicates that, from the late 1970's on, there has been an establishment of many new directed trade relationships mainly between countries that had already been trading in the opposite direction, rather than between countries that had not been trading at all. That is, the reciprocation process of unidirectional trade channels has dominated the formation of new trade relationships between non-interacting countries.

The above results have implications for the evolution of the symmetry properties of the network. The equiprobability symmetry of the configuration model³ allows a statistical interpretation of the real undirected WTW. Higher order topological variables can be explained by the degree sequence. The invariance of the connection probability between vertices is preserved through time, as reflected by the stationarity of undirected link density (connectance). The stationarity is however disrupted as we change lens and move from the undirected to the directed graph. Reciprocity determines a clear symmetry breaking in the directed analogue of the above invariance, as the in- and out-degrees alone are no longer enough to characterise the network. The intensity of this symmetry breaking evolves in time, as evident in the trend of the reciprocity $r(t)$, and even more of $\rho(t)$. The adjacency matrix suddenly starts becoming *more symmetric*: A and A^T become more and more similar in time, indicating that the WTW has undergone a strong evolution towards higher levels of link reversal symmetry of the first type (transpose equivalence).

3.2 Symmetry breaking in the embedding space

A first natural explanation of the above empirical result could be looked for in an overall increase in the number of directed trade relationships during the period considered, a possibility consistent with the globalisation process. In order to understand whether the observed increase in reciprocity is merely due to the overall increase in link density, we formerly stressed the importance of using ρ instead of r since the former washes away density effects. Since in this case the link density $a(t)$ changes in time, using $\rho(t)$ instead of $r(t)$ is also important in order to correctly quantify the temporal evolution of the reciprocity. In fig.3, besides $r(t)$, we also show the evolution of $\rho(t)$. Unlike $r(t)$, the behaviour of $\rho(t)$ is informative and clearly shows that the increase in density cannot explain the increase in reciprocity. Remarkably, the evolution of $\rho(t)$ is even more pronounced than that of $r(t)$, indicating that the change in density determines an underestimation of the steep increase in reciprocity, if the latter is measured by r rather than by ρ . The same consideration applies even if one takes into account the fact that, according to our results discussed above, the increase in the density of directed trade relationships has occurred differentially across world countries, i.e. not uniformly as in a directed random graph model with increasing connection probability $p(t)$ but rather as in a directed configuration model with heterogeneous probabilities $p_{ij}(t)$. If the observed increase in reciprocity were merely due to a differential, rather than homogeneous, increase of link density, then we would observe $r_{ij} \approx p_{ij}$. By contrast, the uniformity of r rules out this possibility. In other words, the inadequacy of the random graph model and the configuration model in reproducing the observed properties of the WTW rules out the possibility that the increase in reciprocity is due to the globalisation process, at least the

³ The configuration model is a maximally random graph ensemble where the degrees of all vertices, i.e. the degree sequence $\{k_i\}$, are specified. In terms of the adjacency matrix A of the graph, the degree of vertex i is $k_i = \sum_j a_{ij}$, and the total number of links is twice the sum of the degrees of all vertices: $L = \sum_{i < j} a_{ij} = \sum_i k_i / 2$. Therefore specifying the degree sequence automatically fixes also the total number of links, which confirms that this model is more constraining than the random graph one.

component of the latter that is responsible for an (either homogeneous or differential) increase in the density of directed trade relationships⁴.

As a second hypothesis, one could consider the establishment of new trade agreements (preferentially between countries that had only unidirectional trade relationships, and determining the reciprocation of the latter) as a possible explanation for the increase in the density of reciprocated links. However, trade agreements do not explain the uniformity of the conditional connection probability $r_{ij}(t) = r_o(t)$. For all years, the latter is empirically found to be the same across all pairs of vertices, which is in contrast with what expected from the formation of trade agreements: an increased value of $r_{ij}(t)$ for pairs of countries signing the agreement, determining an increased heterogeneity of $r_{ij}(t)$ across all pairs. Therefore the evolution in r cannot be explained by the formation of trade agreements. The uniformity of the conditional connection probability also indicates that other factors such as size, distance, etc. appear to be not enough in order to explain how the reciprocity of world trade has evolved.

The above considerations show that the reciprocation of preexisting unidirectional relationships appears to have occurred massively, however with no preference for nearby or richer countries, and in a way which cannot be traced back to an overall increase in the number of trade relationships and trade agreements. We stress again that all these factors must have had an impact on international trade patterns, especially on the intensity of trade relationships, however at a purely topological level they appear to be dominated by a different mechanism, which is uniform across all pairs of countries. In simplified terms, the evolution of the reciprocity of the WTW could be approximated by a process where, with time-varying but country-independent probability, a unidirectional trade relationship existing at time t becomes reciprocated in the following year.

3.3 From a Fordian to a post-Fordian space

Among the possible underlying mechanisms that could generate this process, we must look for one displaying a temporal trend which is synchronous with the one followed by the reciprocity of the WTW and shown in fig.3. To this end, it is useful to recall that in the case of the WTW, vertices and links are samples of vertices and links of a larger underlying network. Indeed, countries themselves do not trade; rather, firms and consumers trade. Hence there are at least two submerged, and much larger, networks: one of goods - final products - and one of production factors - raw materials and semi-products (together with a third network related to the service market). The WTW may be considered as an overlapping map of these two networks. While the two hypotheses advanced above mainly concerned the network of final products, one could look for an explanation relative to the production network (a network composed by factories as vertices and productive means as links). The hypothesis that symmetry breaking occurred in the economic space of the industrial sector in a period starting between the 1970's to the early 1980's, with a significant worldwide impact on the productive structure, has been recently advanced [Ruzzenenti and Basosi(2008a), Ruzzenenti and Basosi(2008b)]. This transition was due on one hand to decreasing energy costs of transport means and on the other hand to raising labor costs. Firms therefore were stimulated to provide production factors outside the division and began dispersing the productive chain outside the company boundaries, sometimes abroad. This process, named by economists *outsourcing*, transformed the space of firms from a Euclidean space, where providers were separated from the production plant by physical distances, to an economic space where physical distances were secondary to other variables (i.e., changed the metric of economic space) [Ruzzenenti and Basosi(2009)]. This process was further reinforced by specialization and technological enhancement, and was one of the driving forces of globalisation. Note that, when a firm extends its productive chain outside the national boundaries, new links may appear in the trade network. This process can determine an

⁴ For further details see [Ruzzenenti et al.()Ruzzenenti, Garlaschelli, and Basosi]

increase in reciprocity, if the new countries entering the production process already import from the firm's country. This mechanism can therefore provide a candidate explanation, from the production side of network flows, for the observed increase in reciprocity, which is also temporally consistent with the empirical trend. If this hypothesis, which must be further investigated, is correct, we would have faced a symmetry breaking in economic space affecting topological space, partially determining the phase transition we observe, and at the correct moment in time.

4. CONCLUSIONS

The unspoken assumption so far adopted was that complex networks can be approached with the tools of statistical mechanics, as if they were thermodynamics systems composed by particles' populations. Indeed analogies can be stressed out, to begin with considering links as particles and vertices as states, whereby a particle may occupy a state when a link exist in between to vertices, to end with the Grancanonical/Microcanonical ensembles, when restrictions over the maximum number of links or the degree sequence, are removed or imposed. Can analogies go further to engulf energy as a measurable quantity of our systems, rather than a merely descriptive device? That is to say, will it ever be possible to associate with every macrostate a specific energy value? This achievement is still far to come, perhaps because we must bear in mind that we are dealing with complex systems, whose overlapping complex network represents just a map. We may be able to define all the possible network states, it is though questionable if they match with all the possible underling system's configurations. Nevertheless, in the present work we wanted to show how statistical mechanics of networks can be employed to rigorously define on what basis we can exclude certain phenomena to be correlated. That is giving a statistical meaning to a causal relationship upon the evolution of the system under investigation. It is of course of particular interest a remarkable phenomenon such a symmetry breaking, in terms of evolutionary pattern, as it underlies major changes in system structure. The fact, for example, that by means of statistical mechanics of network we were able to prove that after the 1970's the WTW increased the intensity of its relationships, by increasing the reciprocity of its network, gave us an intriguing clue about the real causes behind *globalization* and the following dramatic increase in transport energy consumption. A new configuration of the trade network became available to shipments, as if in a transition phase there is the uprising of new states, formerly unavailable, to system's particles, whereby energy can be distributed. This a similar phenomenon in physics to the so-called (macro)*rebound effect* in economics: although the single device or transport mean (particle) is more efficient, the whole system consumes more. This may happen because a new configuration of the system creates the condition for a more intensive particle interactions. We would like to finish with a quotation by Lotka, who probably first envisaged the need for a statistical mechanics of complex (evolutionary) systems.

It would seem, then, that what is needed is an altogether new instrument; one that shall envisage the units of biological population as the established statistical mechanics envisage molecules, atoms and electrons; that shall deal with such average effects as population density, population pressure, and the like, after the manner in which thermodynamics deal with the average effects of gas concentration, gas pressure, etc.; that shall accept its problems in terms of common biological data, as thermodynamics accepts problems stated in terms of physical data; and that shall give the answer to the problem in the terms in which it was presented. What is needed, in brief, is something of the nature of what has been termed *Allgemeine Zustandslehre* a general method or Theory of States'[Lotka(1956)]

REFERENCES

- [Barrat et al.(2008)Barrat, Barthelemy, and Vespignani] A. Barrat, M. Barthelemy, and A. Vespignani. *Dynamical Processes on Complex Networks*. Cambridge University Press, 2008.
- [Caldarelli(2007)] G. Caldarelli. *Scale-Free Networks: Complex Webs in Nature and Technology*. Oxford University Press, Oxford, 2007.
- [Fagiolo(2007)] G. Fagiolo. "Clustering in complex directed networks". *Phys. Rev. Lett.*, 2007.
- [Garlaschelli and Loffredo(2005)] D. Garlaschelli and M. Loffredo. "Structure and evolution of the world trade network". *Phys. Rev. Lett.*, 2005.
- [Garlaschelli and Loffredo(2006)] D. Garlaschelli and M. Loffredo. "Multispecies grand-canonical models for networks with reciprocity". *Phys. Rev. Lett.*, 2006.
- [Garlaschelli and Loffredo(2004a)] D. Garlaschelli and M. Loffredo. "Patterns of link reciprocity in directed networks". *Phys. Rev. Lett.*, 2004a.
- [Garlaschelli and Loffredo(2004b)] D. Garlaschelli and M. Loffredo. "Fitness-dependent topological properties of the world trade web". *Phys. Rev. Lett.*, 2004b.
- [Garlaschelli et al.(2007a)Garlaschelli, Capocci, and Caldarelli] D. Garlaschelli, A. Capocci, and G. Caldarelli. "Self-organized network evolution coupled to extremal dynamics". *Nature Physics*, 2007a. 10
- [Garlaschelli et al.(2007b)Garlaschelli, Di Matteo, Aste, Caldarelli, and Loffredo] D. Garlaschelli, T. Di Matteo, T. Aste, G. Caldarelli, and M. Loffredo. "Interplay between topology and dynamics in the world trade web". *Eur. Phys. J. B*, 2007b.
- [Gross and Sayama(2009)] T. Gross and H. Sayama. *Adaptive Networks*. Springer/NECSI, Cambridge, 2009.
- [Harary(1994)] F. Harary. *Graph Theory*. Addison-Wesley, 1994.
- [Lin(2001)] S. K. Lin. "The nature of the chemical process. 1. symmetry evolution - revised information theory, similarity principle and ugly symmetry". *Int. J. Mol. Sci.*, 2:10–39, 2001.
- [Lotka(1956)] A. Lotka. *Elements of Mathematical Biology*. Dover Publications, Inc, New York, 1956.
- [Mainzer(2005)] K. Mainzer. *Symmetry and Complexity: the Spirit and Beauty of Nonlinear Science*. World Scientific Publishing: Singapore, 2005.
- [McLuhan and Powers(1989)] M. McLuhan and B. Powers. *The Global Village: Transformations in World Life and Media in the 21st Century*. Oxford University Press, 1989.
- [Prigogine(1977)] Y. Prigogine. *Time, structure and fluctuations*, 1977. URL http://nobelprize.org/nobel_prizes/chemistry/laureates/1977/prigogine lecture.pdf.
- [Richard(2009)] C. Richard. "McLuhan and spatial communication". *Western Journal of Communication*, 63(3): 348–363, 2009.
- [Rosen(1975)] J. Rosen. *Symmetry Discovered. Concepts and Applications in Nature and Science*. Cambridge University Press, 1975.
- [Ruzzenenti and Basosi(2008a)] F. Ruzzenenti and R. Basosi. "The rebound effect: An evolutionary perspective". *Ecological Economics*, 67:526 – 537, 2008a.
- [Ruzzenenti and Basosi(2008b)] F. Ruzzenenti and R. Basosi. "The role of the power/efficiency misconception in the rebound effect – A size debate: Does efficiency actually lead to a power enhancement?" *Energy Policy*, 2008b.
- [Ruzzenenti and Basosi(2009)] F. Ruzzenenti and R. Basosi. "Complexity change and space symmetry rupture". *Ecological Modelling*, pages 1880–1885, 2009.
- [Ruzzenenti et al.(2009)Ruzzenenti, Garlaschelli, and Basosi] F. Ruzzenenti, D. Garlaschelli, and R. Basosi. "Complex networks and symmetry: a review with applications to the evolution of world trade". Preprint - submitted to *Symmetry Journal*. URL <http://arxiv.org/abs/1006.3923v1>.
- [Spiekermann and Wegener(1996)] K. Spiekermann and M. Wegener. "Trans-european networks and unequal accessibility in europe". *European Journal of Regional Development (EUREG)*, 1996.

THE EFFECTS OF ENERGY-SAVING TECHNOLOGICAL CHANGE ON ENERGY CONSUMPTION: ASSESSING THE REBOUND EFFECT

Jaume Freire González*

ENT Environment and Management, C/Sant Joan 39, 1, 08800 Vilanova i la Geltrú (Barcelona).

Department of Applied Economics, Autonomous University of Barcelona, Campus de Bellaterra. Edifici B, 08193 Bellaterra (Barcelona).

ABSTRACT

Energy efficiency policies have a special importance within carbon emission reduction policies to mitigate the climate change effects. However, potential reductions of energy consumption –and, consequently, its resulting emissions– can be offset through the so called “rebound effect”. The concept of “rebound effect” includes a set of mechanisms that make an improvement of efficiency to reduce the cost of the energy service that has been improved, and this leads the consumption to rise and totally or partially compensate the reduction achieved by the energy efficiency improvement. This paper carries out a survey of the main studies around the world about empirical evidence of direct rebound effect, focused on household energy consumption, an analysis of the main theoretical developments for the construction of empirical models, and an approximation through econometrical analysis of the extent that direct rebound effect may achieve in Catalan households for electricity consumption. The main results for Catalonia (Spain) show an estimated direct rebound effect of 36% in the short term and 49% in the long term. The paper also show a methodology based in generalised input-output of energy modelling in order to empirically assess indirect rebound effects of energy efficiency improvements in households.

Keywords: electricity consumption; energy efficiency; energy Input-output analysis; rebound effect

1. INTRODUCTION

The rebound effect is a term used to describe the mechanisms whereby a lower cost in the “energy services”, due to an improved technical efficiency, cause the consumer behaviour to change, either at individual or aggregate level. The effect may translate into a longer utilization of energy service, more consumers using the service or into a greater service quality –for example, more powerful cars, with more features, etc.–. This causes the initial reduction of energy consumption be partly compensated or even increased. The existence of the rebound effect is widely accepted by economists dealing with energy issues. The real controversy lies in the identification of sources and size of the rebound (Greening *et al.*, 2000). The question of the magnitude has a vital importance, since most policies for improving energy efficiency are based on the premise that increased energy efficiency leads to lower total energy consumption, and therefore, lower emissions of greenhouse gases.

The literature identifies four types of rebound effects that encompass the microeconomic and macroeconomic perspectives (Greening *et al.*, 2000; Dimitropoulos and Sorrell, 2006; Sorrell, 2007): direct rebound effect, indirect rebound effect, economy-wide and transformational effects. This article focuses on the direct and indirect rebound effect from a static perspective.

The direct rebound effect occurs when an improvement in energy efficiency for a particular energy service reduces the effective cost of the service, which subsequently

* E-mail addresses: jfreire@ent.cat, jaumefreire@hotmail.com; Tel and fax: +34-93-893-5104

leads to increased consumption. This partly or fully offsets the expected reduction in energy consumption. The indirect rebound effect occurs when the reduction of the effective cost of the energy services lead to changes in demands of other goods, services and productive services that also require energy for their provision. Economy-wide effects are the addition of direct and indirect effects and transformational effects are more complex changes in behaviours and other aspects.

The aim of this paper is to show a methodological approach to estimate direct rebound effect for energy household uses through the consistent estimation of energy demand functions and to estimate indirect rebound effect through an environmental Input-output modelling. There is a lack of empirical evidence in this area.

2. LITERATURE REVIEW ON REBOUND EFFECT

Len Brookes defined the rebound effect in general terms, including the economy-wide effects (Brookes, 1978). The direct rebound effect was first defined by Daniel Khazzoom as direct increase on demand for energy services as a result of improvements in technical efficiency in the use of energy (Khazzoom, 1980). Since then, two opposing positions appeared regarding the magnitude of the rebound effect: those who think that the consumption of energy, after the efficiency improvement, is greater than if there had not been efficiency improvement, that is, "backfire"; and those who argue that energy consumption is less than if there had not been efficiency improvement, and energy savings are achieved.

As regards to direct rebound effect in households, there are several studies that provide evidence of space heating and the main results of estimates. In all cases, the direct rebound is significant and less than 100%, but there is a great dispersion in the estimations. Domestic space cooling is one of the less studied cases in empirical literature on direct rebound effect. Energy consumption for space cooling is generally less than the consumption for other uses, but it has experienced significant growth over the last decade. Domestic lighting is another area for which empirical literature on direct rebound effect has been studied. Finally, there is little empirical evidence of direct rebound effect for other end domestic uses. These include water heating, electronic devices and some appliances such as refrigerators, washers, etc. For all these areas there are difficulties when identifying and measuring their energy consumption, since there are few data available.

Table 1 shows some studies that provide evidence of the direct rebound effect associated with space heating, space cooling, lighting and other household end uses. In all cases, the direct rebound is significant and less than 100%, but there is a great dispersion in the estimations.

Table 1. Some empirical evidence of the direct rebound effect associated with household uses

Author	Country	Estimated Rebound Effect
Private transport		
Haughton and Sarkar (1996)	USA	9% - 16% in the short term, 22% in the long term
Greene <i>et al.</i> (1998)	USA	20% in the long term
West (2004)	USA	87%
Small and Van Dender (2005)	USA	4,5% in the short term 22% in the long term
Fronzel <i>et al.</i> (2007)	Germany	56% - 66% in the long term
Space heating		
Khazzoom (1986)	Sacramento (USA)	65%
Schwartz and Taylor (1995)	USA	1.4% - 3.4% in the long term
Hirst (1987)	USA	5% - 25%
Nesbakken (2001)	Norway	15% - 55% (average of 21%)

Guertin <i>et al.</i> (2003)	Canada	29% - 47% in the long term
Space cooling		
Hausman (1979)	USA	4% in the short term and 26.5% in the long term
Dubin <i>et al.</i> (1986)	USA	1% - 26%
Guertin <i>et al.</i> (2003)	USA	34% and 38% in the long term
Set of household energy services		
Guertin <i>et al.</i> (2003)	USA	32% - 49%
Freire González (2010)	Catalonia (Spain)	36% in the short term and 49% in the long term
Washing and drying clothes		
Davis (2007)	USA	< 5%

Source: Own from Greening *et al.* (2000), Binswanger (2001), Sorrell (2007) and Sorrell *et al.* (2009).

Even though direct rebound effects may be low, as seen in existing empirical literature, indirect and economy-wide effects seem to be larger. The evidence on indirect rebound effect is more diffuse. Empirical evidence on indirect rebound effect is almost non-existent and there is no widely accepted methodology to estimate rebound effects in a higher level of aggregation.

Basically, there are four types of empirical studies that have evaluated the indirect rebound effect in the literature (Sorrell, 2007):

1. Elasticity of substitution studies: they consist in carrying out estimations of the elasticity of substitution between energy and capital at different levels of aggregation (Miller, 1986; Stern, 2004; Frondel, 2004).
2. Computable general equilibrium models: these models enable the simulation of impacts, considering the effects on the entire economy –economy-wide effects– (Lenzen, 1998; Allan *et al.* 2006; Barker and Foxon, 2006).
3. Macroeconometrics: such studies are similar to the above, but with the use of econometric models for the estimation of certain parameters of the macroeconomic model (Barker *et al.*, 2007; Junankar *et al.*, 2007).
4. Studies on energy, productivity and economic growth: correspond to a set of empirical studies, including studies on economic history (Fouquet and Pearson, 2006; Richmond and Kaufmann, 2006), neoclassical production theory (Saunders, 2007), ecological economics (Stern, 2000), decomposition analysis (Schipper and Grubb, 2000) and input-output analysis (Sartori and Hestnes, 2007).

Estimations of the energy-embodied content of various categories of goods and services that have increased their consumption due to the indirect rebound effect can be obtained from the input-output analysis, life-cycle analysis (LCA), or a combination of both methods (Chapman, 1974; Herendeen and Tanak, 1976; Jalas, 2002; Cohen *et al.*, 2005; Takase *et al.*, 2005; Carlsson-Kanyama *et al.*, 2005; Kok *et al.*, 2006). Most of these authors indicate that the actual indirect energy requirements in households are larger than the direct energy requirements. One way to estimate this effect is through the “re-sponding” effect of income produced by savings on energy consumption (Sanne, 2000; Chalkley *et al.*, 2001).

3. ESTIMATIONS OF DIRECT REBOUND EFFECT

3.1 Theoretical and methodological aspects of direct rebound effect²

There are some proxy variables that under certain circumstances can be considered a measure of the rebound effect. This is the most common definition used as a measure

² The arguments and demonstrations followed in this section can be found in Becker (1965), Khazzoom (1980), Berkhout *et al.* (2000), Dimitropoulos and Sorrell (2006) and Sorrell (2007).

of direct rebound effect for a particular energy service (Khazzoom, 1980; Berkhout *et al.* 2000; Dimitropoulos and Sorrell, 2006; Sorrell, 2007):

$$\eta_{\varepsilon}(E) = \eta_{\varepsilon}(S) - 1 \quad (1)$$

Where $\eta_{\varepsilon}(E)$ is efficiency elasticity of the demand for energy and $\eta_{\varepsilon}(S)$ is energy efficiency elasticity of the demand for useful work for an energy service. Energy savings due to improved energy efficiency will be based on mathematical model predictions just when the energy efficiency elasticity of the demand for useful work for an energy service will be zero ($\eta_{\varepsilon}(S)=0$), then the energy efficiency elasticity of the demand for energy must be equal to -1 ($\eta_{\varepsilon}(E)=-1$). A positive rebound effect means that $\eta_{\varepsilon}(S) > 0$, so $|\eta_{\varepsilon}(E)| < 1$. From this perspective, given the case that $\eta_{\varepsilon}(S) > 1$ –that is, the demand was elastic–, it would be a case of "backfire" (Saunders, 1992).

Under certain assumptions, measures of rebound effect can be obtained from price elasticities estimations. The following expression can be obtained (Berkhout *et al.*, 2000):

$$\eta_{\varepsilon}(E) = -\eta_{P_S}(S) - 1 \quad (2)$$

A variation of equation (2) has been used for Khazzoom (1980), Binswanger (2001) and Greene *et al.* (1999) to estimate direct rebound effect, since it is easier to implement than equation (1). This definition is based on two assumptions: (1) symmetry: consumers respond the same way to a decrease in energy prices than to improvements in energy efficiency, (2) exogeneity: energy efficiency is not affected by changes in energy prices ($\eta_{P_E}(\varepsilon) = 0$).

Symmetry assumption has key implications since the estimation of direct rebound effect is performed through the estimation of price elasticities. Direct changes in prices could be more perceptible than the effect of efficiency improvement. The hypothesis that energy efficiency is not affected by energy prices is reasonable in periods of stability or decrease of energy prices, but not in periods of increase in energy prices, because they induce technological improvements that remain when prices fall (Dargay, 1992; Grubb, 1995; Sorrell, 2007). Endogeneity is a circularity, that is, energy efficiency affects energy costs and energy costs affects energy efficiency. This can be addressed empirically through the estimation of simultaneous equation models, instrumental variables or analysing cointegration relations between variables.

Due to data availability, equation (2) is often most used to obtain estimations of direct rebound effect than equation (1), since in this case data on energy efficiency is not required. But data on energy demand is more commonly available than data on useful work of a particular energy service, so –since $P_S = P_E / \varepsilon$, considering that energy efficiency is constant– an alternative definition of the rebound effect based on price-elasticity of energy demand ($\eta_{P_E}(E)$) (Dimitropoulos and Sorrell, 2006; Sorrell, 2007) can be obtained:

$$\eta_{\varepsilon}(E) = -\eta_{P_E}(E) - 1 \quad (3)$$

The possibility of obtaining estimates of the rebound effect only from household energy consumption data and energy prices, opens a wide range of possibilities, as well as the consideration of a series of studies that have performed price-elasticity estimations of energy consumption without the explicit consideration of the rebound effect.

3.2 Econometric model and results for Catalonia³

Following Khazzoom (1980), in empirical analysis the meaning of direct rebound effect will be limited at the microeconomic level. At this level, a technological improvement in energy consumption would reduce, *ceteris paribus*, the price of energy services provided by devices that have improved their efficiency. Many economists have used the price elasticity of energy demand as a proxy variable of rebound effect, since Khazzoom suggested this in 1980. This variable allows performing an indirect estimation of rebound effect, that is, without energy efficiency data. Given the availability of data, and as Haas and Biermayr (2000) indicate, the price and income elasticities can be estimated using the following constant elasticity demand dynamic standard function –from specifying a double-logarithmic functional form–. In general terms it can be formalized as:

$$\ln E_{it} = \mu + \beta_1 \ln P_{E_{it}} + \beta_2 \ln Y_{it} + \beta_3 \ln HDD_{it} + \beta_4 \ln E_{it-1} \quad (4)$$

where E_t is the energy consumption in period t ; P_{E_t} is the price of energy in period t ; Y is the income variable; HDD is the climatic variable –in this case the heating and/or cooling degree-days–; and E_{t-1} is the energy consumption in period $t-1$. This last variable captures the long-term effects.

In Catalonia data are available on total household electricity consumption at municipal level, domestic electricity prices and domestic natural gas prices at constant 2003 prices –these two variables do not vary between municipalities, but vary over time–, household disposable income at constant 2003 prices and heating degree-days from 43 municipalities for the period 1991-2002. Chosen base temperature was 21°C.

Table 4. Fixed Effects Model (FEM) total electricity demand in households. Panel of municipalities from Catalonia. Generalized Least Squares (GLS) estimation (cross-section weights)

Variable*	Coefficient	Std. Error	t-Statistic	Prob.
$\ln(P_{E_{it}})$	-0.4946	0.0264	-18.7249	0.0000
$\ln(Y_{it})$	0.4332	0.0366	11.8412	0.0000
$\ln(HDD_{it})$	0.0305	0.0113	2.7061	0.0071
μ	3.3552	0.4219	7.9520	0.0000
Weighted Statistics				
R-squared	0.9999	Mean dependent var		12.35678
Adjusted R-squared	0.9999	S.D. dependent var		5.026793
S.E. of regression	0.0604	Sum squared resid		1.714663
F-statistic	79257.16	Durbin-Watson stat		1.16974
Prob(F-statistic)				

* This table presents only β and μ coefficients, common to all municipalities.

³ This chapter is adapted from Freire González (2010).

Additionally, the model of table 4 has been transformed into an Error Correction Mechanism Model (ECM). This model is the generalization of a partial adjustment model – equation (5)– with lags on endogenous and on exogenous variables, obtaining an estimation in differences:

$$\Delta \ln E_{it} = \delta_1 \Delta \ln P_{E_{it}} + \delta_2 \Delta \ln Y_{it} + \delta_3 \Delta \ln HDD_{it} + \delta_4 \Delta \ln E_{it-1} + \tau u_{it-1} + \varepsilon_{it} \quad (5)$$

where u_{t-1} are the residuals resulting from estimations in Table 4, lagged one period –it represents the error correction term–. This new model has been estimated for GLS –with cross-section weights–, with the estimated coefficients common to all municipalities.

Table 4 with the FEM in levels provides estimations of long-term elasticities, while Table 5 for the ECM model provides estimations of short-term elasticities.

Table 5. Error Mechanism Correction Model (ECM) of total electricity demand at households. Panel of municipalities of Catalonia. Generalized Least Squares (GSL) estimation (cross-section weights).

Variable	Coefficient	Std. Error	t-Statistic	Prob.
$\Delta \ln(P_{E_{it}})$	-0.3568	0.0594	-6.0096	0.0000
$\Delta \ln(Y_{it})$	0.4299	0.0851	5.0519	0.0000
$\Delta \ln(HDD_{it})$	0.0198	0.0101	1.9639	0.0502
$\Delta \ln(E_{it-1})$	0.1062	0.0364	2.9173	0.0037
u_{it-1}	-0.5719	0.0448	-12.7552	0.0000
Weighted Statistics				
R-squared	0.42693	Mean dependent var		0.04638
Adjusted R-squared	0.42154	S.D. dependent var		0.06115
S.E. of regression	0.04651	Sum squared resid		0.91937
F-statistic	79.15	Durbin-Watson stat		1.80161
Prob(F-statistic)	0.0000			

The results lead to estimations of direct rebound effect of 36% in the short term and of 49% in the long term for all energy services that use electricity in households. An increase in energy efficiency of these energy services potentially leading to savings in electricity consumption of 10, would actually produce savings of 6.4 in the short term and of 5.1 in the long term.

4. INDIRECT REBOUND EFFECT AND ENERGY INPUT-OUTPUT ANALYSIS

In order to estimate the overall rebound effect is important to consider indirect, economy-wide and transformational effects. Indirect effects can be addressed through energy input-output. This chapter details a methodology to obtain estimations of static indirect rebound effect. This is based on the development of a generalized Input-output model for energy.

4.1 Methodology for static indirect effects

The energy Input-output model assumes the following approach:⁴ let e be a matrix of direct sectoral consumption of different sources of energy –or the vector of direct sectoral electricity consumption in our case– which is necessary for the production of the goods of the productive system, and let x be the vector of sectoral production. Then a vector of sector intensities in the use of energy can be calculated:

$$E = e x^{-1} \quad (6)$$

where E represents a set of coefficients of energy intensities, whose element E_i represents the energy consumption required for the production of a monetary unit of good i . From equation (6) we can deduce that:

$$e = E x \quad (7)$$

Moreover, we can express Leontief model as:

$$x = (I - A)^{-1} y \quad (8)$$

where the expression $(I - A)^{-1}$ is the Leontief inverse matrix and y represents the vector of sectoral final demand. If x in (7) is substituted by its value in (8), then:

$$e = E (I - A)^{-1} y \quad (9)$$

In this case, $E (I - A)^{-1}$ is a lineal operator which transforms final demand into energy consumption. This model obtains, under certain circumstances, the total energy consumption –direct and indirect– that the overall economic system requires due to a change in the final demand of one or more economic sectors. This effect would be the indirect rebound effect if the change in the final consumption pattern is due to an improvement in energy efficiency.

4.2 Re-spending model

Before using the energy Input-output framework it will be necessary to quantify the variations in the final demand when energy efficiency is improved in households. This can be addressed by defining a previous econometric model that estimates cross-section elasticities between energy efficiency and demand of other goods. An AID (almost ideal demand system) can be used to obtain the new final demand that will be introduced in the energy Input-output model (Brännlund *et al.*, 2007). Because of the lack of necessary data to conduct this analysis, it is possible to calculate the monetary savings of energy efficiency improvements and assume this increase of disposable income is “re-spent” in other goods and services that need energy to be produced (Sanne, 2000; Chalkley *et al.*, 2001). This approach provides several possibilities to allocate the new disposable income among the new budget of households.

⁴ See Leontief and Ford (1970), Chapman (1974), Bullard and Herendeen (1975), Casler and Wilbur (1984), Proops (1988), Alcántara (1995), Lenzen (2001).

5. CONCLUSIONS AND FURTHER RESEARCH

The main objective of this paper was to provide a methodology to estimate the rebound effect for energy household uses. This is based in energy demand functions for direct rebound effect, and in energy Input-output modelling to obtain estimations of static indirect rebound effect. For Catalonia a positive direct rebound effect has been found, but its magnitude is less than 1. The results are consistent and similar with those found in empirical literature on direct rebound effect for the same energy services in other industrialized countries. It would be necessary to estimate the indirect, economy-wide and transformational effects to obtain the magnitude of energy efficiency improvements in households.

Indirect rebound effect can be addressed through an environmental Input-output methodology for energy. The re-spending model may provide the monetary savings to introduce in the Input-output model under assumptions of new consumption patterns.

The results of the estimations have important implications for energy policy. If no measures are undertaken to control the rebound effect, the results show a reduction of the effectiveness of energy efficiency policies in households, in reducing greenhouse gas emissions, and in allocating public resources.

REFERENCES

- Alcántara, V., 1995. *Economía y contaminación atmosférica: hacia un nuevo enfoque desde el análisis input-output*. Doctoral thesis. University of Barcelona.
- Allan, G., N. Hanley, P. G. McGregor, J. Kim Swales, Turner, K., 2006. *The macroeconomic rebound effect and the UK economy*. Final report to the Department Of Environment Food and Rural Affairs, Department Economics, University of Strathclyde, Strathclyde.
- Barker, T., P. Ekins, Foxon, T., 2007. "Macroeconomic effects of efficiency policies for energyintensive industries: the case of the UK Climate Change Agreements, 2000-2010". *Energy Economics*, 29(5), 760-78.
- Barker, T., Foxon, T., 2006. *The macroeconomic rebound effect and the UK economy*. Report to the Department of the Environment, food and Rural Affairs, 4CMR, Cambridge.
- Becker, G.S., 1965. "A theory of the allocation of time". *The Economic Journal*, LXXV (299), 493–517.
- Berkhout, P.H., Muskens, J. C., Velthuijsen J. W., 2000. "Defining the rebound effect". *Energy Policy*, 28, 425–432.
- Binswanger, M., 2001. "Technological progress and sustainable development: what about the rebound effect?" *Ecological Economics* 36 (1), 119–132.
- Brännlund, R., Ghalwash, T., Norström, J., 2007. "Increased energy efficiency and the rebound effect: effects on consumption and emissions". *Energy economics*, 29, 1-17.
- Brookes, L.G., 1978. "Energy policy, the energy price fallacy and the role of nuclear energy in the U.K." *Energy Policy* 6, 94–106.
- Bullard, C. W., Herendeen, R. A., 1975. "The energy cost of goods and services". *Energy Policy* 3(4), 268–278.
- Carlsson-Kanyama, A., Engstrom, R., Kok, R., 2005. "Indirect and direct energy requirements of city households in Sweden". *Journal of Industrial Ecology* 9 (1–2), 221–236.
- Casler, S., Wilbur, S., 1984. "Energy input–output analysis—a simple guide". *Resources and Energy* 6, 187–201.
- Chalkley, A. M., E. Billett, Harrison, D., 2001. "An investigation of the possible extent of the re-spending rebound effect in the sphere of consumer products". *The Journal of Sustainable Product Design*, 1, 163-170.
- Chapman, P., 1974, "Energy costs: a review of methods". *Energy Policy*, 2(2), 91-103.
- Cohen, C., Lenzen, M., Schaeffer, R., 2005. "Energy requirements of households in Brazil". *Energy Policy* 33, 555–562.
- Davis, L. W., 2007. "Durable goods and residential demand for energy and water: evidence from a field trial", *Working Paper, Department of Economics, University of Michigan*.
- Dargay, J. M., 1992. *Are price & income elasticities of demand constant? The UK experience*, Oxford Institute for Energy Studies, Oxford, U.K.

- Dimitropoulos, J., Sorrell, S., 2006. "The Rebound effect: Microeconomic Definitions, Extensions and Limitations". *Proceedings of the 29th IAEE International Conference, Potsdam, Germany*.
- Dubin, J. A., Miedema, A. K., Chandran, R. V. 1986. "Price effects of energy-efficient technologies: a study of residential demand for heating and cooling". *Rand Journal of Economics* 17(3), 310–325.
- Freire González, J., 2010. "Empirical evidence of direct rebound effect in Catalonia". *Energy Policy* 38 (5), 2309-2314.
- Fouquet, R., Pearson, P., 2006. "Seven centuries of energy service: the price and use of light in the United Kingdom (1300–2000)". *The Energy Journal* 27 (1), 139–176.
- Fronzel, M., 2004. "Empirical assessment of energy price policies: the case for cross price elasticities". *Energy Policy*, 32, 989-1000.
- Fronzel, M., J. Peters, Vance, C., 2007. "Identifying the rebound: issues and empirical evidence from a German household panel". *RWI Discussion Papers* No. 57 Essen.
- Greene, D.L., Kahn, J., R. C. Gibson, R. C., 1998. *Estimating the rebound effect for household vehicles in the U.S.* Oak Ridge National Laboratory, Oak Ridge, TN.
- Greene, D.L., Kahn, J., Gibson, R.C., 1999. *An Econometric Analysis of the Elasticity of Vehicle Travel with Respect to Fuel Cost per Mile using the RTEC. Survey Data.* Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Greening, L.A., Greene, D.L., Difiglio, C., 2000. "Energy efficiency and consumption - the rebound effect - a survey". *Energy Policy*, 28, 389–401.
- Grubb, M. J., 1995. "Asymmetrical price elasticities of energy demand", in *Global warming and energy demand*, T. Barker, P. Ekins and N. Johnstone eds, Routledge, London and New York.
- Guertin, C., Kumbhakar, S., Duraiappah, A., 2003. *Determining Demand for Energy Services: Investigating income-driven behaviours.* International Institute for Sustainable Development.
- Haas, R., Biermayr, P., 2000. "The rebound effect for space heating—Empirical evidence from Austria". *Energy Policy* 28(6–7), 403–410.
- Haughton, J., Sarkar, S., 1996. "Gasoline tax as a corrective tax: estimates for the United States, 1970-1991". *The Energy Journal* 17(2), 103–126.
- Hausman, J. A., 1979. "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables". *Bell Journal of Economics*, 10(1), 33–54.
- Herendeen, R., Tanak, J., 1976. "The energy cost of living", *Energy*, 1(2), 165-78.
- Hirst, E., 1987. "Changes in indoor after retrofit based on electricity billing and weather data". *Energy Syst. Policy* 10, 1–20.
- Jalas, M., 2002. "A time use perspective on the materials intensity of consumption", *Ecological Economics*, 41(1), 109-23.
- Junankar, S., Lofsnaes O., Summerton, P., 2007. "MDM-E3: a short technical description". *Working Paper, Cambridge Econometrics*.
- Khazzoom, J.D., 1980. "Economic Implications of Mandated Efficiency Standards for Household Appliances". *Energy Journal*, 1, 21–39.
- Khazzoom, J. D., 1986. *An Econometric Model Integrating Conservation in the Estimation of the Residential Demand for Electricity.* JAI Press, Greenwich, CT.
- Kok, R., R. M. J. Benders, Moll, H. C., 2006. "Measuring the environmental load of household consumption using some methods based on input–output energy analysis: A comparison of methods and a discussion of results". *Energy Policy*, 34(17), 2744-61.
- Lenzen, M., 1998. "Energy and greenhouse gas cost of living for Australia during 1993/94". *Energy*, 23(66), 497–516.
- Leontief, W., Ford, D., 1970. "Environmental repercussions and the economic structure, an input–output approach". *Review of Economics and Statistics*, 52 (3), 262–271.
- Miller, E. M., 1986. "Cross-sectional and time-series biases in factor demand studies: explaining energy-capital complementarity". *Southern Economic Journal*, 52(3), 745–62.
- Nesbakken, R., 2001. "Energy consumption for space heating: a discrete-continuous approach". *Scandinavian Journal of Economics*, 103(1), 165-84.
- Proops, J., 1988. "Energy intensities, input-output analysis and economic development", in: *Input-Output Analysis: current developments*, Ciascini.
- Richmond, A. K., Kaufmann, R. K., 2006. „Is there a turning point in the relationship between income and energy use and/or carbon emissions?" *Ecological Economics*, 56(2), 176-89.
- Sanne, C., 2000. "Dealing with environmental savings in a dynamical economy- how to stop chasing your tail in the pursuit of sustainability". *Energy Policy*, 28(6–7), 487– 495.

- Sartori, I., Hestnes, A. G., 2007. "Energy use in the life-cycle of conventional and low-energy buildings: a review article". *Energy and Buildings*, 39, 249-57.
- Saunders, H. D., 2007. "Fuel conserving (and using) production function". *Working Paper, Decision Processes Incorporated, Danville, CA*.
- Schipper, L., Grubb, M., 2000. "On the rebound? Feedback between energy intensities and energy uses in IEA countries". *Energy Policy*, 28(6-7), 367-88.
- Schwartz, P. M., Taylor, T. N., 1995. "Cold hands, warm hearth?: climate, net takeback, and household comfort". *Energy Journal* 16(1), 41-54.
- Small, K. A., Van Dender, K., 2005. *A study to evaluate the effect of reduced greenhouse gas emissions on vehicle miles travelled. Prepared for State of California Air Resources Board, the California Environment Protection Agency and the California Energy Commission*, Final Report ARB Contract Number 02-336, Department of Economics, University of California, Irvine.
- Sorrell, S., 2007. *The rebound effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. UK Energy Research Centre, London.
- Sorrell, S., Dimitropoulos, J., Sommerville, M., 2009. "Empirical estimates of the direct rebound effect: A review", *Energy policy* 37(13), 1356-1371.
- Stern, D. I., 2000. "A multivariate cointegration analysis of the role of energy in the US macroeconomy". *Energy Economics*, 22, 267-83.
- Stern, D. I., 2004. "Elasticities of substitution and complementarity". *Working Paper a Economics, No. 0403, Rennsselaer Polytechnic Institute*.
- West, S. E., 2004. "Distributional effects of alternative vehicle pollution control policies". *Journal of Public Economics*, 88, 735-57.

COMMUNICATING EMERGY ANALYSIS AS FOOTPRINT AND EMERGY PROFILE

*Anna Levin**

*Department of Social and Economic Geography
Uppsala University*

ABSTRACT

Tools highlighting our attention to human impact on nature and humans accelerating depletion of natural resources, such as fossil fuels, are important in making a change towards a more sustainable way of living. Emergy analysis is a scientific and robust method feasible to appraise the degree of sustainability of human systems. In spite of the advantages of the method, a public breakthrough takes place slowly. One reason could be that the results of an emergy analysis are difficult to grasp. This study aims to assess the degree of sustainability of an agricultural system in central Sweden by means of emergy analysis, and explore effective communication of this information. By demonstrating the results of the analysis in the form of a footprint and emergy profile, a better understanding of the outcome may be achieved. The footprint, here called emergy-based footprint, visualizes all resources used in the production system. The emergy profile shows the emergy flows of the most important items in the system. Alternative visualizations of the agricultural system were created in the study, each scenario presented in an emergy-based footprint as well as in an emergy profile. Together, they show the characteristics of the different production systems. This model may serve as an accessible and communicative guide when trying to transform the Swedish agricultural system, as well as agricultural production worldwide in the direction of sustainability. The model is applicable in general system as well.

Keywords: Resource use, sustainability, communicative, emergy-based footprint, emergy profile

INTRODUCTION

In our modern western worldview we live in a paradigm of fragmentation. The attitudes in society is to separate nearly everything in different boxes. If your roses get infected by leaf lice you immediately control them with some chemicals, instead of strengthen the health of the roses so that they can resist the leaf lice by themselves. In school it is a norm to carry out studies in separate subjects. It is a long tradition, nearly a rule, in at least natural science to define a problem and carry on the research of a delimited part of the problem. The scientific advances during the last decades have been great, maybe as a result of this “tunnel vision”, but the progression is within each discipline, not between them. We can say that the knowledge is tenser in the separate boxes of discipline. We often look upon these boxes as pieces that hypothetical can be joined. But if someone actually will try to put the pieces together they don't fit!

The late Swedish geographer Torsten Hägerstrand wrote on his last book: “at present we behave as children, who draw funny figures on each side of a paper and then get astonished when it is impossible to cut out the figures from one side without avoiding dashing the figures from the other side to pieces. The question of importance in reality is not the perfection of the separate sciences figures. It is rather to find out what sort of paper we are drawing on?” (a free translation from Hägerstrand, 2009)

Within this approach we have to take the responsibility of an accelerating depletion of natural resources, human activities unfavorable influence on the ecological systems on

* E-mail: anna.levin@kultgeog.uu.se

earth (Daily, 1997; Rockström et al., 2009) and an increasing global food demand (www.fao.org). One way of acting in a responsible manner is to increase the sustainability of our society. When dealing with sustainable development it is essential to have an attitude about an entire system, a system in which human beings are nowadays a prominent part. Sustainable development includes a holistic perspective, and while we are finding the direction towards sustainability we have to deal with interactions between and within systems, we have to deal with time and we have to manage different scales. In our fragmented worldview, a sustainable development is a challenge since it is resting up on a holistic way of thinking.

One course of action, to influence the change of attitude towards a more coherent approach is to make use of methods and models that are based on system thinking. Tools that highlight our attention to human impact on nature and the accelerating depletion of natural resources, such as fossil fuels, are of great significance in this changing process. Unfortunately there is a shortage of methods and models aiming at opening our mind to a holistic way of thinking and at the same time have the ability to deal with the complexity of systems. But there exist some; emergy analysis is one of them.

EMERGY ANALYSIS

The theory of emergy has been created during the last four decades in a context of interdisciplinary, involving physics, biology and social science, and most importantly - system ecology and ecology. The fundamental principles of an emergy analysis are the modeling of interactions between factors in a system. Emergy has a holistic and ecocentric viewpoint; components of the system are analysed and quantified, but the definitive result is characterized as a single integrated system. Of importance in systems is the flow of material, information and energy. Consequently, the emergy concept is based on principles of energy. Emergy theory points out that all systems, human system included, are in some way woven together. In an emergy analysis, you can study partition of a system but always have to take inputs and outputs to and from the system in consideration. Emergy analysis puts a value on all work done by the biosphere and transforms them into a common unit, sunemjoule, sej. The model can deal with the totality and the details in the same analysis, as well as with the interactions within the system and the external flows. Emergy analysis is a scientific and robust method, created principally by H.T. Odum during the last four decades (M. T. Brown, 2003; Mark T. Brown & Ulgiati, 2004; H.T. Odum, 1996). Concepts of importance are transformity, energy hierarchy, self organizing system and maximum power principles. To make a result from an emergy analysis clear and possible to compare, a series of indices and ratios are evaluated including a sustainability index, environmental loading ratio, emergy density and renewable- emergy quotient (Björklund & Rydberg, 2003; H.T. Odum, 1996).

In spite of the scientific advantages of the method, the public breakthrough is slow. One possible reason is that the results of an emergy analysis are difficult to grasp. The result from an emergy analysis is presented in figures, in tables, in drawn emergy symbols as well as in indices and ratios. A bald statement of the figures from an emergy analysis may be perceived as very abstract and complex. This makes it difficult to understand the results and implications of an emergy analysis. So a significant weakness for the emergy method is its difficulty to be well communicated (Björklund & Rydberg, 2003).

Emergy-based footprint

In this study a communicative model has been created, aiming at increasing the understanding and appropriation of an emergy analysis. This is done by applying the pedagogical advantage from the concept Ecological Footprint (Wackernagel & Rees, 1996) which visualizes the demand of human activities of the ecosphere in an area. The emergy- based footprint rests upon the calculations from an emergy analysis. The result is then recalculated into an area that visualizes all the resources used in the system. This

area is the one needed if only renewable resources had been used in the system (Björklund & Johansson, 2010; Geber, 2002; Johansson., 2005).

Emergy profile

The emergy profile concept, profit from the realization that almost everybody can imagine the significance of a profile. It describes the system analysed, all resources and flows involved and the magnitude of each component. As concept the emergy profile reminds of the emergy signature (H.T. Odum, 1996, p. 111; Howard T. Odum, 2007, p. 148), the profile is presented by different graphs as the signature. What's separate the profile from a signature is that the profile is showing in a distinct and well arranged way the items in the system within diametrical diagrams. The highest level of classification contains five groups in which the resources are divided in local renewable, local non renewable, global renewable, global non renewable and imported resources covered by money. The five main groups are quantified and expressed in sunemjoule. All of the resources used in each of these main groups can then be traced in the underlying emergy profiles; these profiles express the resources as a percentage. In that way it is possible to follow each group up to a very detailed scale.

A case study

The emergy-based footprint was applied in a case study of a small farm in Sweden. By way of introduction a traditional emergy analysis has been carried out. The result from the analysis was redrafted into an area and a comparison was drawn between current area at the farm and the area needed if all the resources used in the system would have been locally renewable. In this study the locally renewable resources are equivalent to the inflow of rain. An emergy profile was also drawn out of the outcome of the emergy analysis. The same procedure was then repeated for three alternative scenarios for the production system. These alternatives consisted of a conventional, ecological and sustainable production system.

RESULTS FROM THE CASE STUDY

Current production system of the farm

The emergy-based footprint of the actual production system turned out to be relatively big (Fig.1). The resources used in the system were nine times the local renewable resources of the existing farm.

The emergy profile clearly shows the dominance of the imported renewable resources (Fig.2). By tracing the line of the imported renewable resources the profile reveal that the resources of greatest importance were the labour, followed by goat and sheep replacement (Fig.3).

The last biggest group of the five main groups in the profile of current system was the imported non renewable emergy (Fig.2). On a detailed scale this group turned out to consist of a great variety of resources, of most importance had the energy sources as fossil fuels and electricity (Fig. 4).

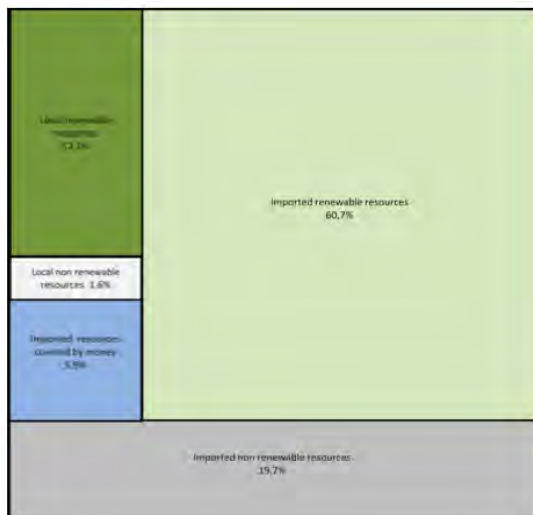


Figure 1. The emergy-based footprint of the current production system of a small farm in Sweden. The relation 1:9 is the quota between the actual area at the farm and the area needed if all the resources used in the system should have been locally renewable.

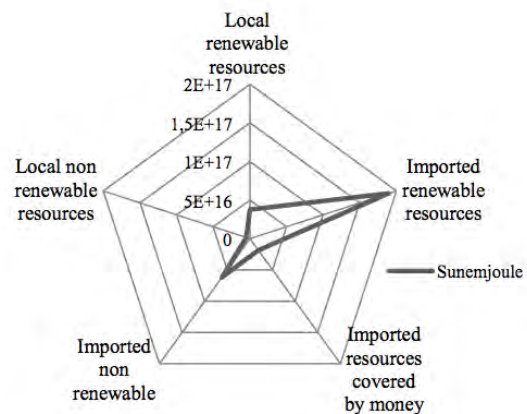


Figure 2. The emergy profile of the five main groups of importance in the case study of a farm in Sweden. Predominant in current production is the input of imported renewable resources. The axes present the resources in the unit of sunemjoule.

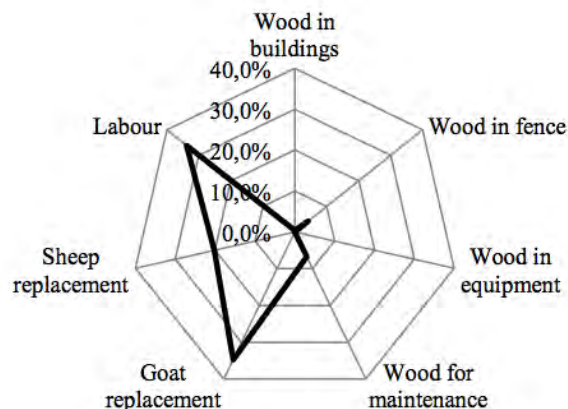


Figure 3. Of the imported renewable resources in the current system of the farm, labour, goat and sheep replacement contributes the dominant part.

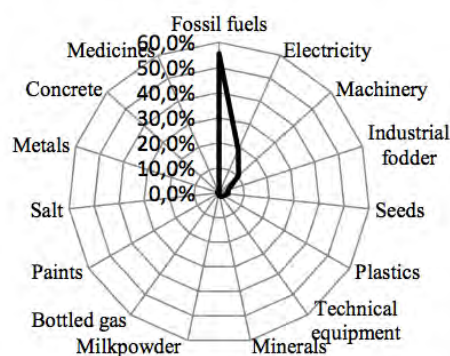


Figure 4. The emergy profile is presenting the organisation of the imported non renewable emergy in current production system. This group consists of a great variety of resources. Of most importance are energy sources such as diesel, petrol and electricity. Machinery is also an input of significance.

Constructed alternative scenario of the production system

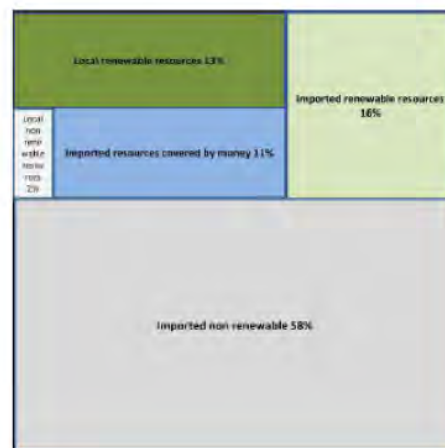
With the purpose of compare different production system three hypothetical productions where created, these were conventional, ecological and sustainable production system of the farm.

If the different designed vision or scenarios of the production were calculated and their emergy-based footprint was placed besides each others, the magnitude of the varying footprints was obvious (Fig 5). In this paper only two of the profiles of the scenarios are presented, i.e. the main profile for the conventional and the ecological production system (Fig. 6 and 8). The conventional and ecological profiles were different from the profile of the current system (Fig. 2,6 and 8) but the conventional and ecological system have an apparent resemblance although the magnitude is different (Fig. 6 and 8). The profile showing the details of the conventional system make clear that artificial fertilizer and fossil fuels contributes with the majority of the inputs in the imported non renewable group (Fig. 7).

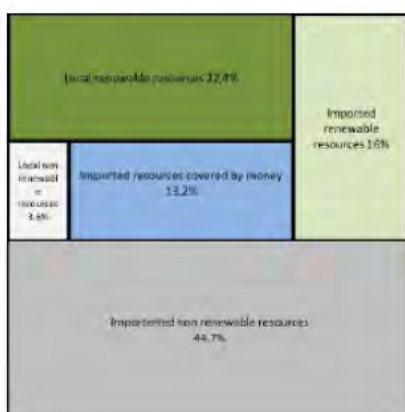
Current production system 1:9



Conventional production system 1:8



Ecological production system 1:4,5



Sustainable production system 1:1



Figure 5. The footprint of the designed scenario for a conventional production system, require a smaller area than the current system. The relation between available resources and the resources made use of in the conventional system is 1:8. A smaller emergy-based footprint is revealed for the ecological system than in the earlier systems, after a recalculation of the emergy input into an area. The relation between available resources and the resources made use of in the ecological system is 1:4,5. An emergy-based footprint made out of a sustainable production system should be balanced with the input from the local renewable emergy. The relation between the actual area and the area corresponding to the resources used were expected to be 1:1.

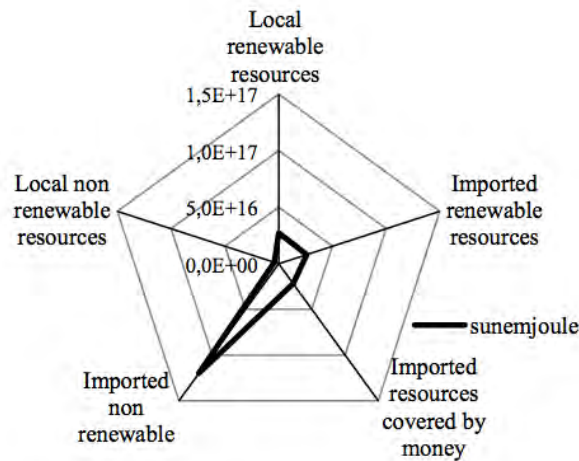


Figure 6. The energy profile of the conventional production system illustrates a profile very different from the current production system. Outstanding in this system is the imported non renewable energy input.

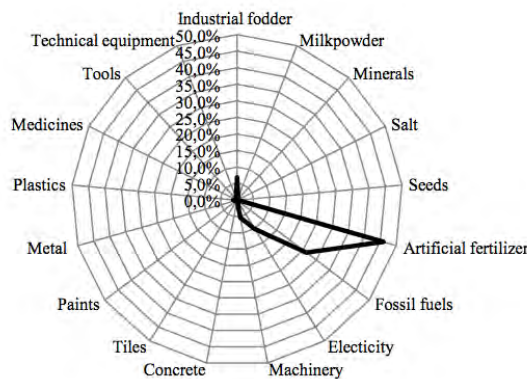


Figure 7. The profile presenting the different resources making up the imported non renewable energy in the conventional system, reveal that the fertilizer and fossil fuels dominate this input.

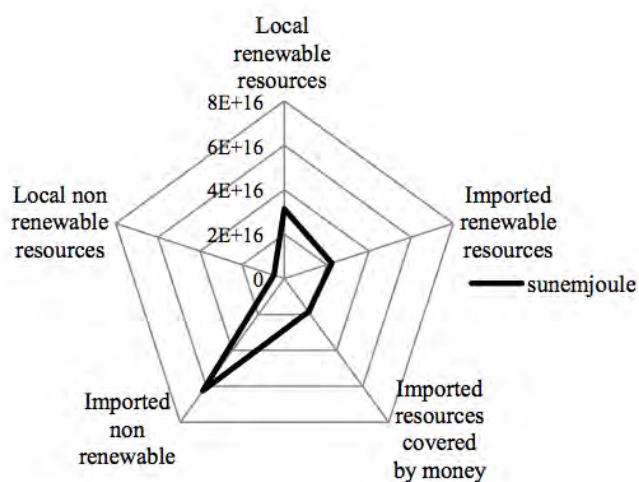


Figure 8. As was the case within the conventional system the imported non renewable resources dominate the profile in the ecological system. But the profile shows an unlikeness from the preceeding since the imported renewable, the local renewable as well as the resources covered by money got a more significant position. The magnitude of the different bars also indicate that the ecological production system, in this case, use less resources than the conventional

DISCUSSION

The emergy-based footprint and the profile of the four production systems seem to be very different. By analyzing these illustrative tools showing the divergence between the production systems determined out of an emergy analysis, a sustainability guide is accessible.

By emergy-based footprint and emergy profile the role of the fossil energy resources will be obvious, fossil resources has an evident position in the imported non renewable group. The magnitude of the fossil energy elucidates obviously in a system analysed by this method. An explanation of this is the transformities values of the fossil resources with put this resource more in reality. With an increased application of such a methodology, the discussion around fossil resources may move from a defined discourse about supply and demand along with carbon dioxide emission and global warming to a more holistic approach dealing with resources in society, now and in the future.

The emergy-based footprint together with the emergy profile can assesses as a scientific and transparent valuation model of systems. Hopefully such presentations are comprehensible and at the same time give readers the possibility to dive in the complexity of the figures and flows in the system analysed. Of course it remains many improvements to put this method in practice. The emergy-based footprint is quite clear and reliable but the emergy profile is in the possession of some teething problems. As an example, one difficulty is the composition of the main groups in the emergy profile. It may be questioned whether the group imported resources covered by money is suitable in this analyse, it is also a problem of vital importance to found out which items fits into the different groups. If profiles will be comparable in a scientific way, there is an advantage if it exist some sort of standardisation in this stage in the method. The name, emergy profile, is at present under revision; a more pedagogical name for this method is in all probability emergy-based fingerprints. It suit well together with emergy-based footprint and is in many situations worldwide more understandable.

On our journey towards sustainability we urgently need methods and models that open our mind to be more "holistic minded" to increase our way of see upon everything as interconnected. We need multiple criteria assessment methodology of sustainability. Emergy- based footprint, jointly with emergy profile is one attempt, one step to create one useful tool, applicable in scientific as in general situations. This method have its theoretical foundation on a stringent and scientific base and in extension of the method, it offers the labyrinth of system theory.

ACKNOWLEDGEMENTS

Thanks to Johanna Björklund at the Swedish University of Agricultural Sciences who inspired me to carry out this study and to Calle and Birgitta Höglund who exposed their farm to this investigation. My supervisors Prof. Göran Hoppe and Jan Boelhouwers have read the texts and giving me constructive-minded advices.

REFERENCES

- Björklund, J., & Johansson, B. (2010). *Assessing multifunctionality in relation to resource use -a holistic approach to measure efficiency, developed by participatory research*.
- Björklund, J., & Rydberg, T. (2003). *Att värdera uthållighet i lantbruket genomgång av metoder för Miljöoch naturresursanalys*. Uppsala: CUL, Swedish University of Agricultural Sciences.
- Brown, M. T. (2003). "Prof. Howard T. Odum 1924 -- 2002". *Energy*, 28(4), 293-- 301.
- Brown, M. T., & Ulgiati, S. (2004). "Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understanding systems". *Ecological Modelling*, 178(1-2), 201-213.

- Daily, G. C. (1997). *Nature's Services, Societal dependence on natural ecosystems*. Washington: Island Press.
- Geber, U. B., J. (2002). "The relationship between ecosystem services and purchased input in Swedish wastewater treatment systems a case study". *Ecological Engineering*, 18 pg39.
- Hägerstrand, T. (2009). *Tillvaroväven*. Stockholm: Forskningsrådet FORMAS.
- Johansson, S. (2005). *The Swedish Foodprint* (No. ISBN 91-- 576-- 6955-- 4). Uppsala: Acta Universitatis Agriculturae Sueciae.
- Odum, H. T. (1996). *Environmental accounting: EMERGY and environmental decision making*. New York: Wiley.
- Odum, H. T. (2007). *Environment, power and society for the twenty-first century : the hierarchy of energy* (New ed.). New York: Columbia University Press.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S. I., Lambin, E., et al. (2009). "Planetary Boundaries: Exploring the Safe Operating Space for Humanity". *Ecology and Society*, 1 34.
- Wackernagel, M., & Rees, W. (1996). *Our ecological footprint*. Gabriola Island: New Society Publishers.
- www.fao.org.
- http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf. Retrieved 20100913

WEALTH, TRADE AND ENVIRONMENT IN BRAZIL AND ITALY. AN EMERGY-BASED COMPARISON OF CARRYING CAPACITY, ECONOMIC PERFORMANCE AND WELLBEING

Lucas Pereira^{*1}, Amalia Zucaro², Enrique Ortega¹ and Sergio Ulgiati²

¹ *Ecological Engineering Laboratory, Food Eng. School, State University of Campinas, Campinas, Sao Paulo, Brazil*

² *Department of Environmental Sciences, Parthenope University, Napoli, Italy*

ABSTRACT

Time and spatial scales matter. Time series analyses have been proven to be useful in capturing tendencies of a country's economical behavior. Large-scale evaluations at national scale are essential to highlight the basic parameters relevant to smaller scale case studies (regional, local, and sectors). Due to the importance and variability of those parameters or indicators over time and spatial scales, national evaluations should be updated every year. The aim of this work is to investigate time series of Brazilian and Italian economies on the basis of the emergy synthesis method, building on existing statistical data and accurate matter, energy and monetary flow assessment. Main objective is to provide comprehensive indicators of carrying capacity, performance and wellbeing over time, pointing out the differences between a developing nation, the economy of which is mainly based on the agricultural sector and raw commodities export (Brazil) and a developed nation characterized by industrial manufacturing, tourism and service sectors (Italy). Focus is placed on emergy indicators capable of accounting for societal metabolism (emergy per capita, emergy per €, emergy per ha, environmental loading ratio, emergy yield ratio) and shedding light on conventional monetary assessments. Trade between Brazil and Italy is also investigated (coffee, soy, wood, sugar, lubricants, parts and accessories of machinery and cars, etc) in order to stress issues of fair and equitable trade in terms of balanced emergy exchange. Emergy indicators showed that the Brazil uses great percentage of renewable resources on the total, resulting in low environmental load and good sustainability, although an oscillation tendency is shown. Results are the opposite for Italy, since it uses large amounts of non-renewable and imported resources. As for the trade between the countries, a huge disparity is shown in terms of emergy values: Brazil exported $4.97\text{E}+22$ seJ to Italy and imported $7.83\text{E}+20$ seJ in 2008.

Keywords: Emergy, Brazil, Italy, trade

1. INTRODUCTION

Time series analyses have been proven to be useful in capturing tendencies of a country's economical behavior. Large-scale evaluations at national scale are essential to highlight the basic parameters relevant to smaller scale case studies (regional, local, and sectors). Due to the importance and variability of those parameters or indicators over time and spatial scales, national evaluations should be updated every year.

Main objective is to provide comprehensive indicators of carrying capacity, performance and wellbeing over time, pointing out the differences between a developing nation, the economy of which is mainly based on the agricultural sector and raw commodities export (Brazil) and a developed nation characterized by industrial manufacturing, tourism and service sectors (Italy).

The purpose of this paper is to discuss emergy-based time series analyses for Brazil (1981, 1989, 1996, and 2008) and Italy (1984, 1989, 1991, 1995, 2000, 2002, and 2008). Values of specific emergy or transformities refer to the $15.83\text{E}+24$ seJ/yr baseline

* Corresponding author; E-mail: lucasgp@fea.unicamp.br; Telephone: +55 (19) 3521-4058

according to Brown and Ulgiati (2004) for all investigated years. Comparison of the two countries in terms of emergy and conventional demographic economic indicators in the year 2008 (population, GDP, GDP per capita) sheds light on standard of life and trade equity. Historical series from published literature are used (Coelho *et al.*, 2003; Cialani *et al.*, 2005; Lomas *et al.*, 2007). Data for 2008 have been generated in the present study.

According to Bargigli *et al.* (2004), conventional economic approaches quantify traded flows in terms of the amounts of goods traded and the money paid for them. The economic assessment of trade very often only focuses on money balance and does not take into proper account the real quality of the traded resources as well as the related environmental problems, both from the point of view of the depletion of resources and of the pollution generated in the exporting country. Resources are very often mined and partially processed in the exporting country, then refined and used in the importing developed countries. The price of exported resources is very often inadequate to compensate for the depletion of local storages and the environmental burden that is generated by resource extraction and primary processing.

Emergy synthesis (Odum, 1996; Brown and Ulgiati, 2004) is capable of providing a global and comprehensive evaluation of human-dominated systems. According to the emergy theory different forms of energy, materials, human labor and economic services are all evaluated on the common basis of biosphere. Emergy-based indicators provide a non-conventional perspective of wealth, trade and environmental performance of a country, since the method is deeply rooted in the concept of resource quality, i.e. the awareness that different energy forms have a different ability to do useful work and support an economy. According to Franzese *et al.* (2009), such an ability (or quality) is an intrinsic feature of the resource and derives from the characteristics of the process that generated the resource itself. The quality of a resource depends on its physical–chemical characteristics, which in turn depends on the work performed by nature to make it. Emergy synthesis focuses on what it takes for biosphere to make and for societies to process a given resource.

2. EMERGY SYNTHESIS

Emergy synthesis (Odum, 1988, 1996, 2007) is an evaluation method rooted in irreversible thermodynamics (Prigogine, 1947; De Groot and Mazur, 1962), and systems thinking (Odum, 1983; von Bertalanffy, 1968). It aims at calculating indicators of environmental performance that include both natural and economic resources supporting ecosystem and human-dominated processes (Ulgiati *et al.*, 1993; Brown and Ulgiati, 1999; Ulgiati, 2001; Rydberg and Haden, 2006).

Emergy is defined as “the total amount of available energy of one kind (most often of the solar kind) that is used up directly or indirectly in a process to deliver an output product, flow, or service” (Odum, 1996). Emergy accounting is a measure of the past and present environmental support to a process, and it allows exploring the interplay of natural ecosystem and human activities.

The ratio of the available energy previously used up to make a product to the actual energy content of such a product provides a measure of the hierarchical position of the item within the thermodynamic scale of the biosphere (a kind of production cost of the item measured in “biosphere currency”). Such a ratio is expressed as solar equivalent Joules per Joule (seJ/J) or per gram (seJ/g), named Unit Emergy Value (UEV) in general, and respectively transformity (seJ/J) and specific emergy (seJ/g). According to such a supply-side perspective, the more energy is previously used up, the higher are a product's transformity and consequently its position in the energy hierarchy (Odum, 1996) of biosphere.

Detailed definitions and calculation procedures may be found on Brown and Ulgiati (2004). Emergy accounting is organized as a top-down approach where first a system diagram of the process is drawn to organize the evaluation and account for all inputs and outflows. Tables of the actual flows of materials, labor, and energy are constructed from

across time or countries, the PPP GDP will be used as a means of calculation and comparison in this work. PPP GDP for selected countries may be found at: <http://www.imf.org/external/pubs/ft/weo/2006/01/data/dbginim.cfm>.

- **emergy density (seJ/ha):** the ratio of total emergy use in the economy to the total area of the country. Brazil and Italy enormously differ in terms of total land, natural preserved, and urbanized areas. The emergy density shows the concentration of the emergy use, a useful indicator of the intensity of activities in that country.
- **Environmental Loading Ratio (ELR):** the ratio of nonrenewable and imported emergy use to renewable emergy use. It is an indicator of pressure of a transformation process on the environment and can be considered a measure of ecosystem stress due to a productive activity.
- **Emergy Yield Ratio (EYR):** the ratio of the total emergy (local and imported) driving a system to the emergy imported. The ratio is a measure of the potential contribution of the process to the main economy, due to the exploitation of local resources.

Comparing conventional demographic and economic indicators is of crucial importance before getting involved in the construction and interpretation of emergy-based indicators. We will therefore start from discussing trends of Population, GDP, Inflation, and GDP *per capita*, that are among the most important and most widely used indicators for the investigation of economic systems at all levels (Lomas *et al.*, 2007).

3. RESULTS

Population growth or stability affects *per capita* indices as well as those indices that are indirectly linked to population dynamics (GDP *per capita*, emergy use *per capita*, etc.). Figure 2 shows the population growth in Italy and Brazil from 1984 to 2008. As it can be observed, population is still increasing in Brazil, while in Italy it has reached a constant level. During the period investigated, Brazilian population has increased more than 45%, compared to an increase of only 4% for Italy. According to IBGE (2004), although population growth rates in Brazil are higher than in developed countries, prevision is that they will reduce in the next years. Growth rate will drop to 0.24% in 2050, and finally to zero in 2062, when population will start to decrease.

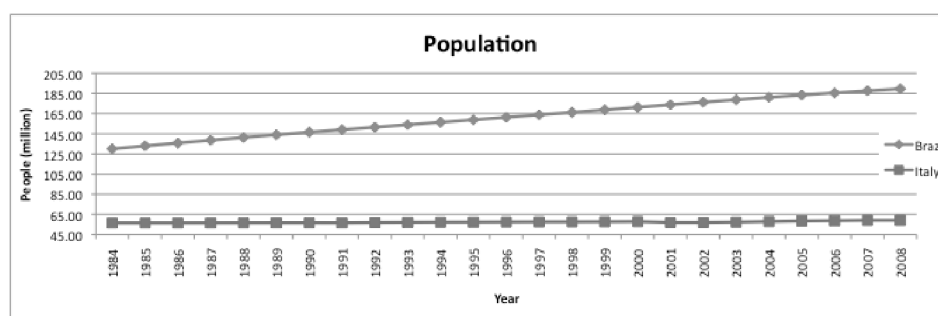


Figure 2. Population growth in Brazil and Italy (1984-2008)

GDP is a measure of the total domestic economic activity. Inflation affects GDP, making it grow even in the absence of a real increase of the global national economic product. According to Lomas *et al.* (2007), calculating emergy-based indicators involving GDP without considering how GDP's dynamics is affected by inflation would make indicators not comparable and unreliable. Inflation affects the real meaning of GDP (Figure 3) and GDP *per capita* (Figures 4). As a consequence, it also affects the values and meaning of Emergy/GDP ratios (Figures 5a and 5b) and emergy exchange ratios (Figure 10). The only way to understand and compare GDP composite emergy-based indicators is to keep clearly in mind the links between GDP and inflation over years. The question is if higher GDPs *per capita* indicate a real progress of buying power. For that

reason, the use of PPP GDP could be a more appropriate numerator for composite indicators.

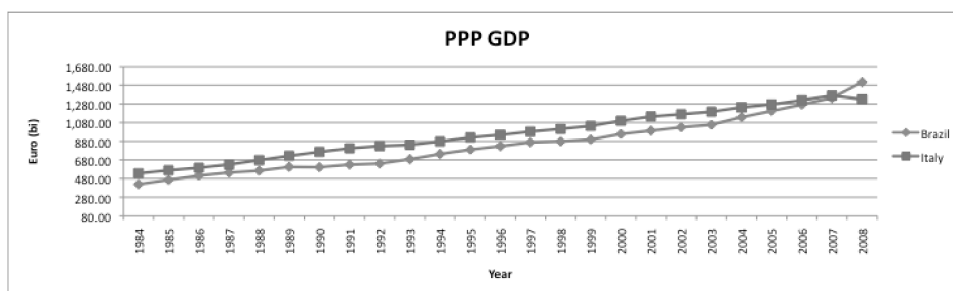


Figure 3. PPP GDP in Brazil and Italy (1984-2008)

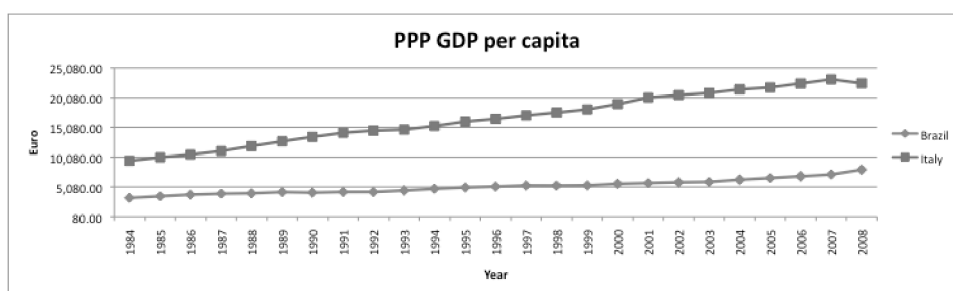


Figure 4. PPP GDP per capita in Brazil and Italy (1984-2008)

Figures 3 and 4 show that PPP GDP and PPP GDP per capita have increased over the selected years for both countries. Brazil has increased its total GDP in the last years, surpassing Italy in 2008. Nevertheless, Brazilian income per capita is still low due to its large population. Figures 5a and 5b indicate a decreasing energy to money ratios, since energy use does not follow the same increasing trend as GDP.

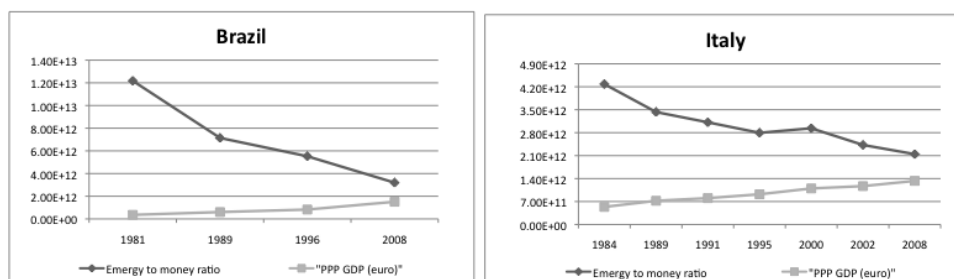


Figure 5a, b. Energy to money ratio and PPP GDP for Brazil and Italy

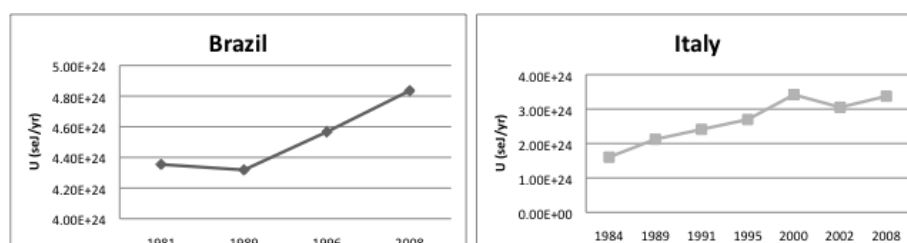


Figure 6a, b. Total energy use U (seJ/yr) for Brazil and Italy.

The total amount of emergy actually used (i.e., the total environmental support directly and indirectly received by a given country) provides a measure of the real size of a country's national economy in the larger frame of the ecosphere (Figure 6a,b). The total emergy used in Brazil was 4.35E+24 seJ in 1981, 4.32E+24 seJ in 1989, and 4.57E+24

seJ in 1996 showing an increasing trend in the period investigated. Same trend is observed for Italy, although with small fluctuations in the last years. In 2008, Italy had a total energy use of $3.37\text{E}+24$ seJ/yr, 30% smaller than Brazil ($4.84\text{E}+24$ seJ/yr). When analyzing Figure 7, emergy use per person, the situation is reversed, with Brazil ranking much lower than Italy. The Brazilian emergy use per capita shows a decreasing trend, while Italy still has an increasing one. This can be explained by the combined effect of different population growth patterns and different life styles in the two countries as well as higher trade benefits to Italy.

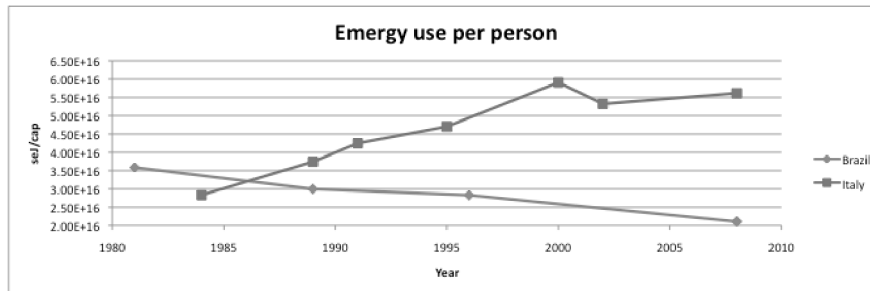


Figure 7. Emergy use per person in Brazil and Italy

Emergy density (seJ/m^2) presented in figure 8 shows the concentration of the emergy use, which can be a useful indicator of the intensity of activities in the country, and suggest land as a limiting factor. Brazilian emergy density is low and constant if compared to increasing Italian values. Brazilian lower density is due to the large amount of land available, but the word “available” should not be misinterpreted. This is not land available for any use, but instead it is land already used in support of the present Brazilian economy, in so reinforcing the country’s carrying capacity. Converting this land to economic uses would increase GDP and decrease carrying capacity and sustainability.

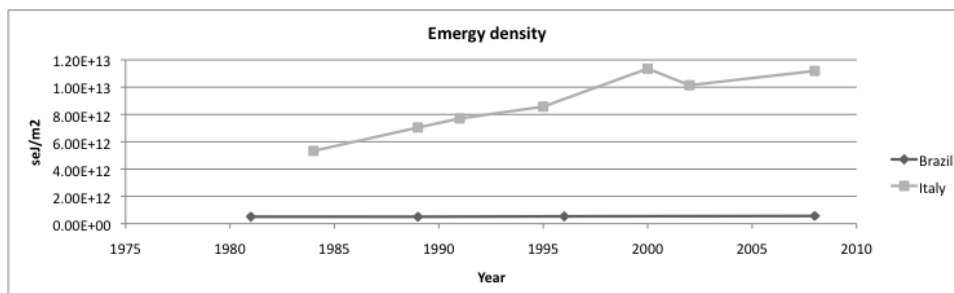


Figure 8. Emergy density in Brazil and Italy

When analyzing figures 9a and 9b, it becomes clear that Brazil is much less dependent on imported economic resources (lower F/Y) than Italy. Another important aspect is that Brazil uses more locally renewable resources (higher R/Y) than Italy in relation to the total emergy use of the country.

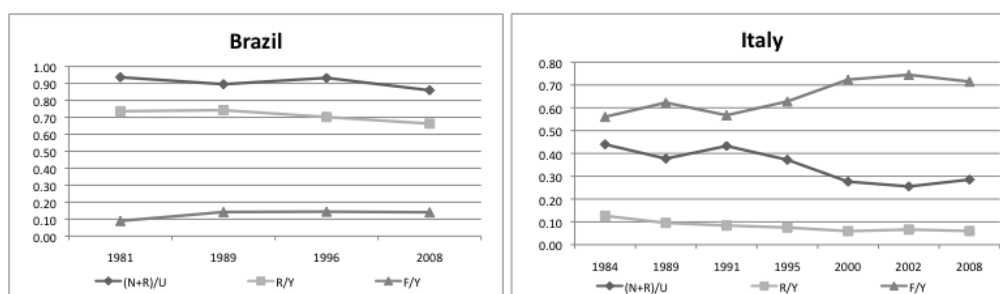


Figure 9a, b. Emergy flows in Brazil and Italy

Figure 10a and 10b show a comparison among the main energy indicators calculated for Italy and Brazil. The Energy Yield Ratio ($EYR = U/F = (R+N+F)/F$) is a measure of the ability of a process to exploit and make local resources available by investing outside resources. The lowest possible value of EYR is 1, by definition. For such a reason, the decreasing value of the indicator over time for both countries indicate a system that performs more as a conversion process of imported resources, than as a harvesting process of new and local resources. The Environmental Loading Ratio ($ELR = (N+F)/R$) calculated for the Italian system is very high (reaching a value of 15.68 in the year 2008), indicating a much higher dependence from non-renewable resources. Instead, the low Brazilian ELR (0.51 in the year 2008) points out a large reliance on renewable inputs. The two parameters combined together provide the Energy Sustainability Index ($ESI = EYR/ELR$), an aggregate measure of economic and environmental performance, that is much lower for the Italian system than for Brazil. ESI for the Italian system decreases steadily by more than 45% (0.09 in year 2008). Same decreasing trend is observed in Brazil, but the absolute value is much higher.

“Terms of trade” is defined as the relationship between the price received for exports and the amount of imports a country is able to purchase with that money as: terms of trade is equal to the ratio “total economic value of exports/total economic value of imports”. It can be useful to show the level of a country's economic dependence on imports, but it doesn't really show the quantity (or mass amount) or quality traded, since price is highly influenced by inflation rates, taxes, technology, and the purchasing power of a country's currency.

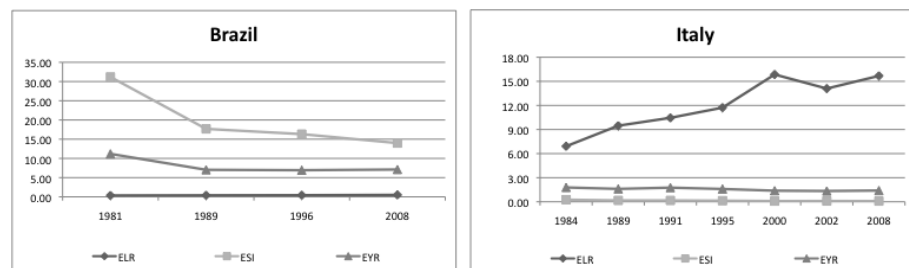


Figure 10a, b. Energy indices for Brazil and Italy

According to Lomas *et al.* (2007), since money only pays for the human labor and services, it is highly unlikely that market price can take into account the “hidden imports” embodied in the products. Energy synthesis provides instead an alternative definition for “terms of trade”, whereby the energy associated to the traded resource is compared to the energy associated to the money received. Each traded product is multiplied by its energy intensity factor (transformity, seJ/J , or specific energy, seJ/g). The total energy exported with the traded raw resources is then compared to the total energy imported with the commodities that can be purchased on the international market thanks to the money received.

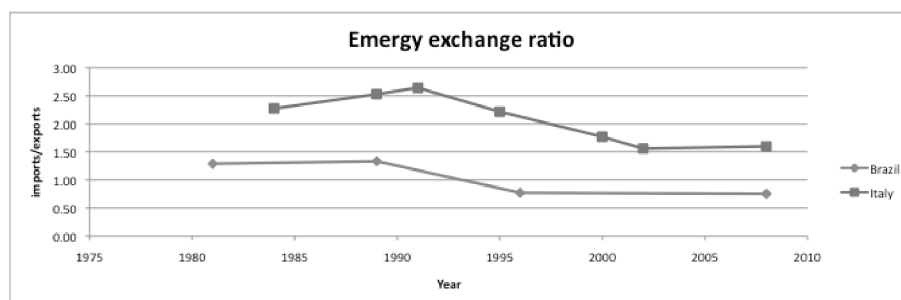


Figure 11. Energy exchange ratio (imported energy/exported energy) in Brazil and Italy

Figure 11 shows that Italy is much more dependent on imports in terms of emergy than Brazil, although there is a tendency of reduction in both countries. In this work we have dealt with two countries with completely different geographic and economic characteristics. In order to have a deeper understanding of those economic differences, a comparison between the trade involving Brazil and Italy was also made, related to the most recent year for which data are available. Table 1 shows the economic value, the quantity and the associated emergy flows of selected products commercialized between the countries.

Table 1. Selected products traded between Brazil and Italy in 2008

Products	Amount (g)	Value (US\$)	UEV [#] (seJ/g)	Ref	Emergy (seJ)
Brazil to Italy					
Soybeans	1.13E+12	4.77E+0	9.87E+09	[a]	1.12E+2
Coffee grains (non-toasted)	1.73E+11	4.77E+0	2.57E+10	[b]	4.45E+2
Round-wood	7.45E+11	4.15E+0	6.79E+08	[c]	5.06E+2
Iron ore agglomerated	4.10E+12	3.79E+0	2.22E+09	[d]	9.09E+2
Iron ore non-agglomerated	6.68E+12	3.13E+0	2.22E+09	[d]	1.48E+2
Leather	1.98E+10	2.06E+0	2.42E+11	[e]	4.80E+2
Refined copper cathodes	2.28E+10	1.59E+0	3.36E+09	[f]	7.66E+1
Bagasse	3.73E+11	1.39E+0	1.97E+08	[g]	7.33E+1
Shoes	2.72E+09	1.21E+0	7.22E+09	[h]	1.96E+1
Corn grains	3.21E+11	7.22E+0	1.45E+10	[a]	4.66E+2
Total of selected products	1.36E+13	2.76E+0			4.97E+2
Total of all products traded*	1.50E+13	4.77E+0			
Italy to Brazil					
Parts for tractors and vehicles	1.48E+10	1.36E+0	4.65E+09	[i]	6.89E+1
Lubricants without additives	8.25E+10	1.00E+0	3.38E+09	[j]	2.79E+2
Parts for vehicles' body	1.32E+10	9.41E+0	4.65E+09	[i]	6.14E+1
Parts of machinery for earth-	1.94E+10	7.74E+0	4.65E+09	[i]	9.03E+1
Gear for vehicles	4.05E+09	6.72E+0	4.65E+09	[i]	1.88E+1
Beta interferon	3.65E+06	5.59E+0	4.25E+10	[k]	1.55E+1
Naphthas for petrochemical	5.35E+10	4.54E+0	4.65E+09	[l]	2.49E+2
Machinery for packaging	8.71E+08	4.27E+0	4.65E+09	[i]	4.05E+1
Other machinery	1.87E+09	4.20E+0	4.65E+09	[i]	8.70E+1
Pharmaceutical drugs	7.25E+07	4.15E+0	4.25E+10	[k]	3.08E+1
Total of selected products	1.90E+11	7.02E+0			7.83E+2
Total of all products traded*	8.03E+11	4.61E+0			

Source: Brazilian Ministry of Development, Industry and Commerce (MDIC, 2008)

*includes all products traded, not only the selected ones

[#]Unit Emergy Value (all values are updated to the 15.83E+24 seJ/yr baseline and include labor and services). Value also includes the emergy supporting labor and services associated to each commodity.

References: [a] Brandt-Williams, 2002; [b] Guillén, 2003 (value of 1.54E+06 seJ/J = 1.54E+06 seJ/J x 4,0 kcal/g x 4186 J/kcal = 2.57E+10 seJ/g); [c] Bastianoni *et al.*, 2001; [d] Buranakarn, 1998 (estimated as iron ore); [e] Odum *et al.*, 1987a (value of 1.44E+07 seJ/J = 1.44E+07 seJ/J x 4,0 kcal/g x 4186 J/kcal = 2.42E+11 seJ/g); [f] Lapp, 1991; [g] Odum and Odum, 1983; [h] Odum *et al.*, 1987b (estimated as rubber); [i] Haukoos, 1995 (estimated as steel products); [j] Odum, 1996 (estimated as crude oil); [k] Odum *et al.*, 2000 (estimated as fertilizer); [l] Haukoos, 1995.

According to Table 1, Brazil exports a total amount of 1.50E+13 g to Italy, and imports 8.04E+11 g. Although the total amount of products exported from Brazil is much higher than the imported, the total economic value is almost the same: US\$ 4.77E+09 and US\$ 4.61E+09 respectively, thus making the conventional terms of trade approximately equal to one.

The application of the Emergy method to traded products in Table 1 shows a very different perspective on trade balance. Brazil exported 4.97E+22 seJ to Italy and only received (for the same economic value) 7.83E+20 seJ in 2008. It means that Brazil receives 5.37E-14 US\$/seJ of commodity exported (or, in other words, invests 1.79E+13

seJ to generate an income of 1 US\$), whereas Italy receives $8.96\text{E-}13$ US\$/seJ of commodity exported (or invests $1.12\text{E+}12$ seJ per US\$ gained).

If we analyze this trade only in terms of total monetary value, it could be considered as a “fair-trade” (Brazil's export/import = 1.03). Considering the quantity (mass), it becomes clear that Brazil exports ten times more products' mass than imports from Italy. This happens, because Brazilian exportation is based on bulk resources that are supplied without qualitative differentiation across the market. Observing the emergy flows for selected products, a huge disparity in the trade (Brazil's exports emergy/imports emergy = 63.47) is shown. Since the monetary value of the trade between Brazil and Italy is almost the same, this suggests that the economy of Italy is supported by resources from Brazil much more than money flows indicate.

4. CONCLUSION

Emergy synthesis was used to account for different forms of energy, materials, human labor and economic services supporting the economies of Brazil and Italy, evaluated on a common basis. Emergy-based indicators have been able to provide a non-conventional perspective of the wealth, trade and environmental performance of these two countries. It is important to highlight that emergy synthesis' results presented as time series analysis are definitely strong and appealing, and allow an integration of emergy indicators with conventional economic indicators such as GDP, income per capita, population growth.

Results show that Brazilian economy is based on export of resources with low aggregated value, while Italy strongly depends on resource imports. Emergy indicators also show that Brazil uses a large percentage of locally renewable emergy resources, translating into a low environmental load and still good sustainability indicators. As for Italy, the opposite is true since the country uses large amounts of non-renewable and imported resources.

The analysis of historical series of emergy flows and indicators was shown in this study to be a very useful and comprehensive tool for the assessment of a country's performance, by bringing into the accounting process important factors such as the environment and the time embodied in resources. The assessment is suggested as a useful complement to conventional economic analyses that only look at market value of resources and processes.

REFERENCES

- Bargigli, S., Cialani, C., Raugeli, M., Ulgiati, S., 2004. “Uneven Distribution of Benefits and Environmental Load. The Use of Environmental and Thermodynamic Indicators in Support of Fair and Sustainable Trade”. In Ortega, E. & Ulgiati, S. (editors): *Proceedings of IV Biennial International Workshop “Advances in Energy Studies”*. Unicamp, Campinas, SP, Brazil. June 16-19, Pages 159-174.
- Bastianoni, S., Marchettini, N., Panzeri, M., Tiezzi, E., 2001. “Sustainability assessment of a farm in the Chianti area (Italy)”. *Journal of Cleaner Production*, 9: 365-373.
- Brandt-Williams, S. L., 2002. *Folio #4. (2nd printing). Emergy of Florida Agriculture. Handbook of Emergy Evaluation. A compendium of data for emergy computation*. Center for Environmental Policy. University of Florida. Gainesville. FL. USA.
- Brown, M.T., Ulgiati, S., 1999. “Emergy evaluation of the biosphere and natural capital”. *AMBIO* 28, 486–493.
- Brown, M.T., Ulgiati, S., 2004. “Emergy analysis and environmental accounting”. In: Cleveland, C. (Ed.), *Emergy*. Academic Press, Elsevier, Oxford, UK, pp. 329–354.
- Buranakarn, V., 1998. *Evaluation of recycling and reuse of building materials using the emergy analysis method*. Ph.D. thesis. University of Florida. Gainesville. FL. USA.
- Cialani, C., Russi, D., Ulgiati, S., 2005. “Investigating a 20-year national economic dynamics by means of emergy-based indicators”. In: Brown, M.T., D. Campbell, V. Comar, S.L. Huang., T. Rydberg, D.R. Tilley, and S. Ulgiati (Eds.) 2004. *Emergy Synthesis. Theory and Applications*

- of the *Emergy Methodology* – 3. The Center for Environmental Policy, University of Florida, Gainesville, FL, 2005. pp. 401-416.
- Coelho, O., Ortega, E., Comar, V., 2003. “Balanço de emergia do Brasil”, in: Ortega, E. (Ed.). *Engenharia ecológica e agricultura sustentável: Exemplos de uso da metodologia energética-ecossistêmica*. [URL: <http://www.fea.unicamp.br/docentes/ortega/livro/index.htm>].
- De Groot, S.R., Mazur, P., 1962. *Non-equilibrium Thermodynamics*. North-Holland, Amsterdam.
- Franzese, P., Rydberg, T., Russo, G.F., Ulgiati, S., 2009. “Sustainable biomass production: A comparison between Gross Energy Requirement and Emergy Synthesis methods”. *Ecological Indicators* 9 (2009) 959–970.
- Guillén, H. A., 2003. “Environmental and economic aspects of agro-forestry and agricultural systems in Chiapas. Mexico”. In: *Proceedings of the Second Biennial Emergy Conference. Center for Environmental Policy. University of Florida. Gainesville. FL. USA*.
- Haukoss, D.S., 1995. *Sustainable architecture and its relationship to industrialized building*. Ph. D. Thesis. University of Florida. Gainesville. FL. USA.
- IBGE. Brazilian Institute of Geography and Statistics. *Population Projection for Brazil. 2004*. [URL: www.ibge.gov.br/home/presidencia/noticias/].
- Lapp, C.W., 1991. *Emergy analysis of the nuclear power system in the United States*. Class report, EES 6916. Environmental Engineering Sciences, under Dr. H. T. Odum supervision.
- Lomas, P.L., Cialani, C., Ulgiati, S., 2007. “Emergy Analysis of Nations: Lessons Learned from Historical Series”. In: Brown, M.T., Campbell, D., Comar, V., Haung, S.L., Rydberg, T., Tilley, D., Ulgiati, S. (Eds.), *Emergy Synthesis*, vol. 4, pp. 39.1-39.18.
- Odum, H.T., Odum, E.C., King, R., Richardson, R., 1987a. *Ecology and economy: emergy analysis and public policy in Texas. Energy systems in Texas and the United States*. Policy research project report number, 78. The Board of Regents. University of Texas.
- Odum, H.T., Wang, F.C., Alexander Jr., J.F., Gilliland, M., Miller, M., Sendzimer, J., 1987b. *Emergy analysis of environmental value. Center for Wetlands*. University of Florida. Publication # 78-17.
- Odum, H.T., 1988. “Self-organization, transformity, and information”. *Science* 242, 1132–1139.
- Odum, H.T., 1994. *Ecological and General Systems: An Introduction to Systems Ecology*, University Press of Colorado, Niwot, Revised Edition of Systems Ecology, 1983, Wiley, p. 644.
- Odum, H.T., Odum, E.C. (Eds.), 1983. *Emergy analysis overview of nations*. International Institute of Applied Systems Analysis. Laxenburg. Austria.
- Odum, H.T. 1996. *Environmental Accounting. Emergy and Environmental Decision Making*. John Wiley & Sons, New York, USA, 370 pp.
- Odum, H.T., Brown, M.T., Brandt-Williams, S., 2000. *Folio #1. Introduction and Global Budget. Handbook of Emergy Evaluation. A compendium of data for emergy computation*. Center for Environmental Policy. University of Florida. Gainesville. FL. USA.
- Odum, H.T., 2007. *Environment, Power and Society for the Twenty-First Century: The Hierarchy of Emergy*. Columbia University Press, USA, 432 pp.
- Prigogine, I., 1947. *Study of thermodynamics of Irreversible Processes*, 3rd ed. Wiley, New York.
- Rydberg, T., Haden, A.C., 2006. “Emergy evaluations of Denmark and Danish agriculture: assessing the influence of changing resource availability on the organization of agriculture and society”. *Agriculture, Ecosystems & Environment* 117, 145–158.
- Ulgiati, S., Odum, H.T., Bastianoni, S., 1993. “Emergy analysis of Italian agricultural system: the role of energy quality and environmental inputs”. In: Bonati, L., Cosentino, U., Lasagni, M., Moro, G., Pitea, D., Schiraldi, A. (Eds.), *Trends in Ecological Physical Chemistry*. Elsevier, Amsterdam, pp. 187–215.
- Ulgiati, S., 2001. “A comprehensive energy and economic assessment of biofuels: when “green” is not enough”. *Critical Reviews in Plant Sciences* 20 (1), 71–106.
- von Bertalanffy, L., 1968. *General System Theory*. George Braziller, New York, NY, 295 pp.

SUSTAINABILITY ASSESSMENT FOR IBIUNA COUNTY, SAO PAULO, BRAZIL THROUGH EMERGY EVALUATION

Elisa Sayoko Nakajima , Lucas Gonçalves Pereira, Enrique Ortega*

*Ecological Engineering Laboratory, Food Eng. School, State University of
Campinas, Campinas, Sao Paulo, Brazil*

ABSTRACT

The neighborhood between Ibiuna and Sao Paulo metropolitan region has become Ibiuna county an important suppliers of horticultures and vegetables for the metropolis and its surroundings. In the past, this proximity to Sao Paulo has lead many families to adopt Ibiuna as a summer resort town, which helped in its economic development. Traditionally, the farms were small vegetables monocultures, but the market economy has raised the costs of the fertilizers and pesticides, causing the purchasing price of the agricultural products to drop and the region's traditional farming has become unviable. Horticulture was tried as a solution, but not too long after being implemented it revealed a similar issue – the hardness in obtaining profit with this activity. As a result of that, many families who lived on agriculture began to sell their land. Many of these lands located near the main highway with access to the city of Sao Paulo have been sold at very low prices, and these areas were occupied by condominiums that do not comply with any environmental laws. In our current days Ibiuna became a dormitory town for people working in the city of São Paulo. The objectives of this study are: (a) conduct a historical survey on the dynamics of the land use in this county, (b) carry on an emergy evaluation of the county considering both the rural and urban areas and (c) compare the emergy indexes of Ibiuna with indexes of other counties.

Keywords: emergy, sustainability, agricultural production, Ibiuna, rural and urban development

1. INTRODUCTION

Part of the economy of several municipalities in the state of Sao Paulo is based on agriculture and provides products for metropolitan areas. In a study of typology according to the GDP of the state, Ibiuna was considered as a relevant agricultural profile to the state. Ibiuna is among the 63 counties that, although, represent 4.6% of the total GDP of the state, account for 35.3% of total added value of the state agriculture (SEADE, 2009).

Ibiuna county is located 72 km west from the capital Sao Paulo and has approximately 70,000 inhabitants of whom 33% live in urban areas and 67% in rural areas. The rural area inhabitants are small producers and many of the farms are classified as family farming systems. The city is located on the slopes of the Sierra Paranapiacaba where there is a forest reserve area of 26,000 hectares called Parque Estadual de Jurupará, Ibiúna owns 95% of it. This preserved area, considered by ONU as a biosphere reserve, is administered by the State Forestry Institute (Municipality Local Government of Ibiuna, 2010).

Ibiuna's climatic conditions - mountain climate, with mild wet winter, created a high demand in the city of Sao Paulo for a second house or recreational farms and / or vacation homes in the vicinity of the dams and the county is a potential tourism city (Gomes, 1997). These facts have also interfered in the process of economic development. Thinking about the future of this city is very worrying, since it can lead to population growth and unsustainable development.

* Corresponding author; E-mail: sayokonakajima@hotmail.com; Telephone: +55(19)3521-4058

The aim of this study is the emergy diagnosis of Ibiuna which was conducted to assess the current sustainability. This study will be useful on another moment for the research of the dynamics of development and to verify the performance of land use and occupation.

2. METHODOLOGY



Historical data of governmental institutions as SEADE (State System of data analysis institute) and IBGE (Brazilian Institute of Geography and Statistics) were employed to obtain additional data for the dynamics of land use. Also, History books of the city were researched and interviews were conducted with the local government officials, as well as with technical staff from the rural electric cooperative in the city.

3. RESULTS AND DISCUSSIONS

In the period from 1960's to 1990's city experienced a moment of great productivity and profits due to the volume of agricultural production. In mid-1990 a virus contamination of the land has forced many farmers to move from the region. Farmers who had under conditions decided to try horticulture. At the end of the 1990's horticulture started to have

high costs because the increasing necessity of chemical fertilizers; the land has become increasingly dependent on this input which became increasingly expensive. Thus, some owners sold their land to other farmers who kept farming activities. Several lands, especially those around the main road, were sold at low prices to the construction of condominiums and rural villages. Table 1 shows Ibiuna largest population growth in absolute figures that happened between the decades of 1990 and 2000 and also shows that after that period until now there were changes on land use.

Table 1. Evolution of the Population of the Municipality of Ibiuna

Year	Population	Absolute Growth
1920	10960	
1940	12423	1463
1950	18072	5649
1960	23465	5393
1970	24270	805
1980	31265	6995
1990	46941	15676
2000	64384	17443
2005	73905	9521

Area A, Figure 2, located around the main road to the city of São Paulo, is plentiful of condominiums in where many homes have become the capital workers dormitory; this is one of the responsible factors of the population growth of Ibiuna. Area B, Figure 2, has second houses condominiums for the middle class people of the suburbs of Sao Paulo and also has agriculture farms. Area C, located in the west, is a luxurious part of the city where resort condominiums for the upper class of São Paulo are situated in the borders of Itupararanga dam. In the south, Area D, has farms with crops and livestock.

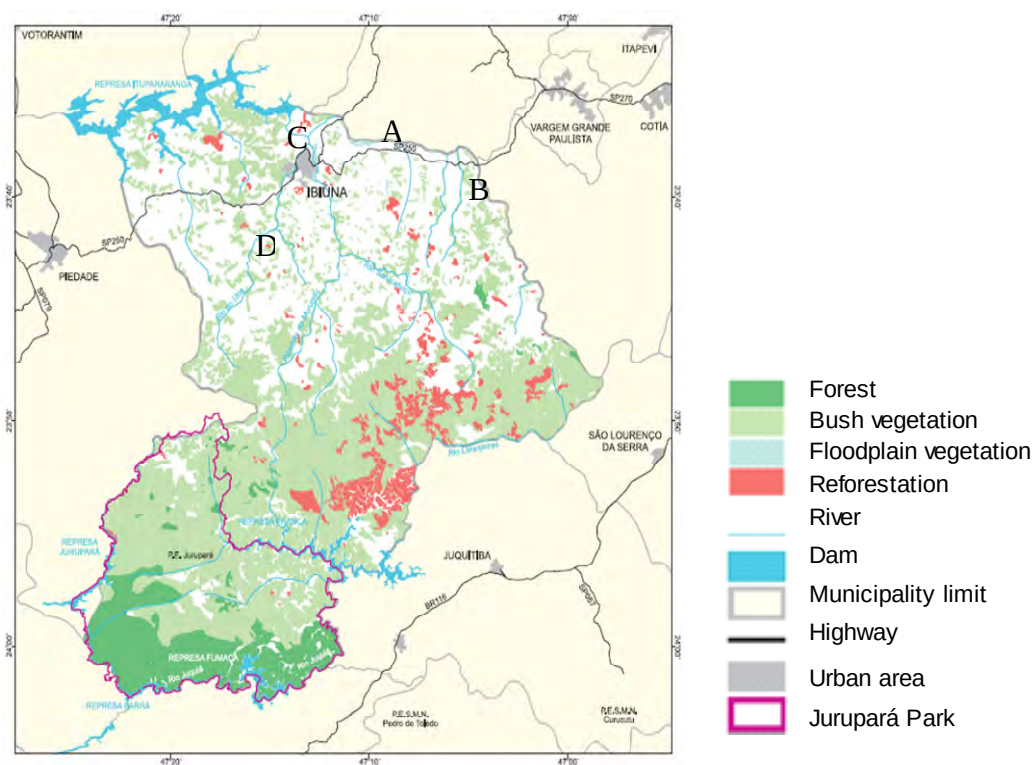


Figure 2. Land use in the county

Rural neighborhoods are another common feature in the county, the population is old and their descendants still live there. These features contributed to the suburbs grow which required more urban infrastructure, like sewage treatment and electricity. One indicator of this growth is the number of rural electricity connections that has been implemented in this period. In the decade of 1990, 4579 consumers were served and in 2000 the number was 10 327 customers. In this number are included rural properties, neighborhoods and condominiums that were emerging in the countryside. In the last decade, until the end of 2009, the number of costumer was 17251, there was a marked households increasing in rural area (CETRIL, 2009). It is noticed that the initial land use was rural, but its profile is becoming more urban year after year.

Although the number of residence has increased in this period, the relative increase in demand in kW was not proportional. The evaluation of the ratio demand/residence in 2000 is equal to 1.36kW/residence while in 2009 it was 1.0 kW/residence, which shows that the rural population performs a better use of electricity.

3.2 Emergy evaluation of the county of Ibiuna considering both the rural and urban areas,

The system diagram represents all the input flows to the county as well as the internal flows.

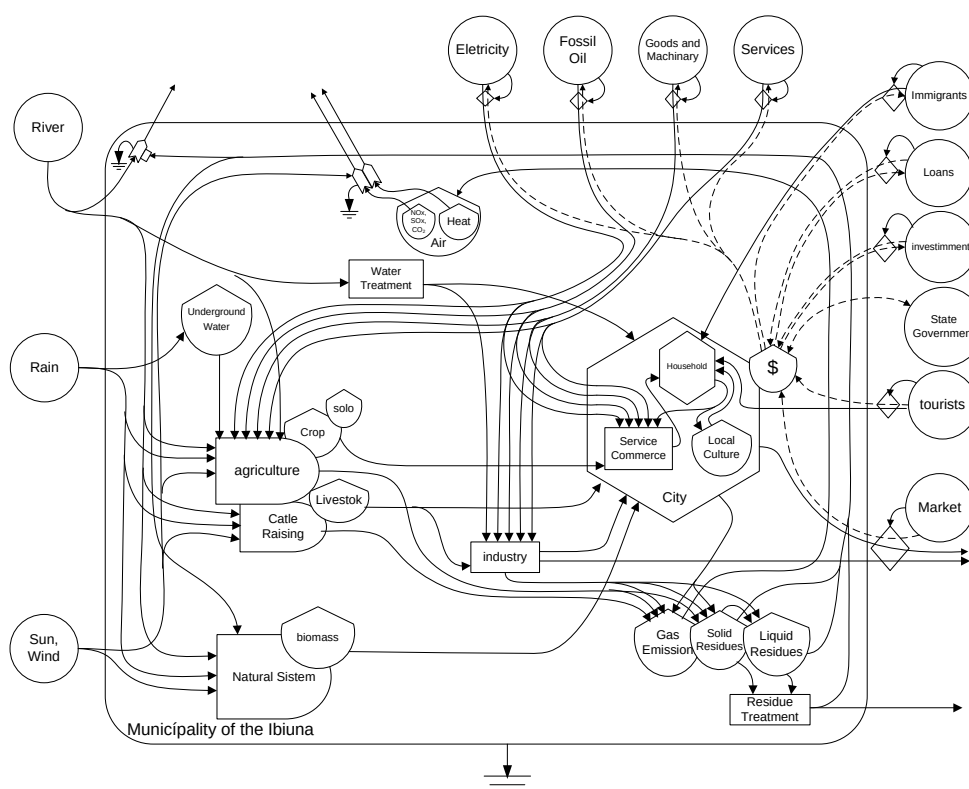


Figure 3. System diagram of the Municipality on the Ibiuna

Table 1 presents the emergy calculations for the county of Ibiuna. Indicators of the preservation area and agricultural one were also calculated as shown in Table 2. According to the estimated data it was verified that the rates of renewability and sustainability for the county are low. But it is important to consider that the data used in this study were converted from the country GDP to the by city GDP; it is possible that there is some deviations that generates the necessity of further analysis. It is supposed

that more detailed input data of the county will provide better values for both sustainability and renewability, whereas the ratio of natural area by the total area is quite significant.

3.3 Comparing the emergy index with other counties.

The comparison of Ibiuna and other cities formerly calculated by other authors, indicates that Ibiuna has a higher sustainability index. For the other indicators, such as EYR, the emergy yield is better and the ELR also presents a less environmental pressure than the other systems, as shown in Table 3.

Table 1. Emergy Flows of Ibiuna County

Items	Unit	Value	FIE (seJ/unit)	Refs	Emergy (seJ/ano)	% Emergy (with L&S)	% Emergy (without L&S)
Renewable Inputs (locally available)							
1 Sun	J/year	6.60E+18	1	[a]	6.60E+18	0.06%	0.51%
2 Wind	J/year	1.83E+16	2.51E+03	[b]	4.60E+19	0.39%	3.57%
3 Rain	J/year	3.08E+15	3.05E+04	[b]	9.41E+19	0.80%	7.29%
5 River	J/year	2.02E+15	8.14E+04	[b]	1.65E+20	1.40%	12.78%
6 Rivers Geopotencial	J/year	4.00E+15	4.66E+04	[b]	1.86E+20	1.58%	14.45%
Non-renewable inputs(locally available)							
7 Soil erosion	J/year	1.41E+14	1.23E+05	[c]	1.74E+19	0.15%	1.35%
Imported input							
8 Gas oil	J/year	1.11E+15	1.11E+05	[b]	1.23E+20	1.04%	9.56%
9 Natural Gas	J/year	3.82E+14	8.05E+04	[b]	3.08E+19	0.26%	2.39%
10 Coal	J/year	1.68E+14	6.71E+04	[b]	1.13E+19	0.10%	0.88%
11 Uranium U308	J/year	9.59E+13	3.01E+03	[b]	2.88E+17	0.00%	0.02%
12 Hydroelectric	J/year	3.87E+14	2.67E+05	[b]	1.03E+20	0.88%	8.02%
13 Ethanol	J/year	5.15E+14	1.28E+05	[d]	6.60E+19	0.56%	5.11%
14 Electricity	J/year	4.42E+13	3.36E+05	[b]	1.49E+19	0.13%	1.15%
15 Foods							
15a Fish	J/year	1.65E+12	5.88E+06	[e]	9.72E+18	0.08%	0.75%
15b Meat	J/year	2.97E+13	2.87E+06	[f]	8.53E+19	0.72%	6.62%
15c Fruits	J/year	2.53E+13	4.82E+05	[f]	1.22E+19	0.10%	0.95%
15d Dairy products	g/year	5.25E+09	3.37E+10	[g]	1.77E+20	1.50%	13.72%
15e Cereals	g/year	5.25E+09	1.63E+09	[h]	8.56E+18	0.07%	0.66%
15f Sugar	J/year	1.14E+14	1.43E+05	[f]	1.62E+19	0.14%	1.26%
16 Iron and Steel	g/year	2.94E+11	4.25E+06	[i]	1.25E+18	0.01%	0.10%
17 Paper	g/year	2.36E+09	6.55E+09	[c]	1.54E+19	0.13%	1.20%
18 Fertilizers	g/year	7.29E+09	6.37E+09	[b]	4.64E+19	0.39%	3.60%
19 Cement	g/year	1.51E+10	3.48E+09	[d]	5.25E+19	0.44%	4.07%
Services							
20 Import Services from within Brazill	US\$/year	1.33E+08	2.24E+12	[j]	9.39E+20	7.95%	
21 Import services from external	US\$/year	2.05E+09	2.24E+12	[j]	8.27E+21	70.02%	
22 Human labor	US\$/year	3.25E+08	2.24E+12	[j]	1.31E+21	11.10%	

References: [a] per definition; [b] Odum, 1996 (updated after Odum et al., 2000); [c] Brown & Arding,1991 (updated after Odum et al., 2000); [d] Brown & Ulgiati, 2004; [e] Hammer, 1991 (updated after Odum et al., 2000); [f] Ulgiati et al., 1993 (updated after Odum et al., 2000); [g] Brandt-Williams, 2002; [h] Brown & McClanahan, 1996 (updated after Odum et al., 2000); [i] Luchi & Ulgiati, 2000 (updated after Odum et al., 2000) and [j] this work.

Table 2. Emergy index – Urban , natural and rural area

		IBIÚNA	Preserved area	Agriculture
Area	ha	106,000	31,930	8,642
Population	person	72,029		44,802
GRD	US\$	319,444,444		53,240,741
GRD per person	US\$/person	4,435		1,188
Total Emergy (com L&S)	seJ	1.14E+22	5.20E+19	9.21E+20
Emergy per person	seJ/person	1.58E+17		1.73E+13
Emergy Density	seJ/ha	1.08E+17	1.63E+15	1.07E+17
Emergia pelo PIB	seJ/US\$	3.57E+13		1.73E+13
EYR		1.40		1.02
ELR		19.27	0.02	65.82
Renewability (R/Y)		4.37%	98.07%	1.50%

According to the experience of ecological farmers, a family needs at least 4 ha in area and carrying capacity. Comparing the carrying capacity of the Brazilian cities studied, it was observed that Ibiuna shows higher values than Campinas.

Table 3. Ibiuna county Emergy Index compare with other county

		IBIÚNA (2008)	CAMPINAS (2008)	ROMA (2002)	MACAO (2004)	BEIJING (2004)
Area	ha	106,000	79,570	125,800	2,750	1,680,000
Population	pessoas	72,029	1,061,290	2,540,000	465,333	14,900,000
GRD	US\$	319,444,444	15,088,888,889	72,513,888,889	972,777,778	50,500,000,000
GRD per person	S\$/person	4,435	14,217	28,549	2,090	3,389
Total Emergy (com L&S)	seJ	1.14E+22	8.15E+22	1.08E+23	2.46E+22	6.50E+23
Emergy per person	eJ/pessoa	1.58E+17	7.68E+16	4.25E+16	5.28E+16	4.36E+16
Emergy Density	seJ/ha	1.08E+17	1.02E+18	8.59E+17	8.94E+18	3.87E+17
EYR		1.40	1.40	1.02	0.74	1.52
ELR		19.27	65.40	60.43	904.00	492.57
Renovabilidade (R/Y)		4.37%	1.29%	0.37%	2.90%	0.30%
Carrying Capacity	ha/family	5.89	0.30	0.20	0.02	0.45

4. CONCLUSION

In this study it was observed that to preserve Ibiuna county sustainability or even to restore it, it is mandatory to monitor the processes of occupation and land use, to avoid uncontrolled population growth in order to not exceed the limits of carrying capacity of the region . Public policies are necessary to control immigration, and perhaps, it is necessary even to think about a population decline.

ACKNOWLEDGEMENTS

Local officials Mauro Issler, César Augusto de Oliveira, Fernando Salles, Daniel Issa, the engineer Arnaldo Pardo Leite Jr of the Casa da Lavoura and Engineer Alberto Hilario Ferreira da CETRIL by the attention and information transferred. Especially for Cida ribas and her team Fernando and Gustavo partnership.

REFERENCES

- Ascione, M., Campanella, L., Cherubini, F., Ulgiati, S., 2009. "Environmental Driving Forces of Urban Growth and development An Emergy-based assessment of the City of Rome, Italy". *Landscape and Urban Planning*, 93: 238-249 p.
- Brandt-Williams, S.L., 2002. *Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued In a Series of Folios. Folio 4. Emergy of Florida Agriculture*. Center for Environmental Policy. University of Florida, Gainesville, Florida, USA.
- Brown, M.T. & J. Arding. 1991. "Transformities" *working paper. Center for Wetlands. University of Florida. Gainesville. FL. USA.*

- Brown, M.T., Ulgiati, S., 2004. *Emergy Analysis and Environmental Accounting, Encyclopedia of energy*, 2:329-354
- Brown, M.T., Mcclanahan, T.R. 1996. "Emergy Analisis Perspectives of Thailand and Mekong River dam Proposal". *Ecological Modelling*, 91: 105-130 p.
- CETRIL (*Rural electric cooperative in the city*) Report of the Board-year 2000
- CETRIL (*Rural electric cooperative in the city*) Report of the Board-year 2009
- Gomes, J. 1997 – *Y Una Noiva Azul. História do município de Ibiuna*. Editora Tempos Ltda.
- Hammer, M. 1991. "Sweden's herring fisheries: A comparison between coastal, offshore and industrial fisheries". In: *Emergy analysis: a biophysical bridging between the economies of humanity and nature*. Nilsson, P.O. & Doherty, S.J. (eds.). A report of initial studies to Vattenfall and the Royal Academy of Agricultural Sciences, Stockholm. Sweden.
- IBGE, Brazilian Institute of Geography and Statistics –. Accessed in 27/05/2010. www.ibge.gov.br.
- Lei, K., Wang, Z., Ton, S. 2008. "Holistic Emergy analisis oh Macao". *Ecological Engineering*, 32: 30–43 p
- Luchi, F. & Ulgiati, S. 2000. "Energy and emergy assessment of municipal waste collection. A case study". In: *Proceedings of the First Biennial emergy analysis research conference*. Brown (Ed.). Center for Environmental Policy. University of Florida. Gainesville. FL. USA.
- Odum H. T. 1996. *Environmental Accounting. Emergy for environmental decision making*. John Wiley & Sons, Inc., New York, USA.
- Odum, H.T., Brown, M.T., Brandt-Williams, S.L., 2000. *Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued In a Series of Folios. Folio no. 1*. Introduction and Global Budget. Center for Environmental Policy. Environmental Engineering Sciences, University of Florida, Gainesville, Florida, USA.
- Prefeitura de Ibiuna (Municipality Local Government of Ibiuna), available em: [site:http://www.ibiuna.sp.gov.br/turismo/tab_historico.html](http://www.ibiuna.sp.gov.br/turismo/tab_historico.html) :
- SEADE. *The State System of Data Analysis*. Available in: . Available in: <http://www.seade.gov.br/produtos/perfil/perfil.php>. . Accessed in 28/07/2010.
- SEADE. *The State System of Data Analysis* .Available in: http://www.seade.gov.br/produtos/pibmun/pdfs/PIBMunicipal_Tipologia_metodologia.pdf Accessed in 28/07/2010
- Zhang, Y., Yang, Z., Yu, X. 2009. "Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China)". *Ecological Modelling*, 220: 1690–1696 p

AN EMERGY ASSESSMENT OF WORLDWIDE BIOGEOCHEMICAL FORMATION OF COAL, OIL AND NATURAL GAS

Mark T. Brown^{*1}, Gaetano Protano², and Sergio Ulgiati²

¹ University of Florida, Gainesville, USA

² Parthenope University of Naples, Italy

ABSTRACT

The work invested by the geobiosphere to generate the global storages of fossil energy resources is assessed in this study by means of the Emergy Synthesis method. The analysis relies on published estimates of historic, global net primary production (NPP) on land and oceans, published preservation and conversion factors of organic matter, and assessments of the present total global storages of coal, petroleum, and natural gas. Results show that the production of coal resources over geologic time required between 6.63 E4 ($\pm 0.51 \text{ E4}$) seJ/J and 9.71 E4 ($\pm 0.79 \text{ E4}$) seJ/J , while, oil and natural gas resources required about 1.48 E5 ($\pm 0.07 \text{ E5}$) seJ/J and 1.71 E5 ($\pm 0.06 \text{ E5}$) seJ/J , respectively. These values are between 1.5 to 2.5 times larger than previous estimates and acknowledge a far greater power of fossil fuels in driving and shaping modern society.

Keywords: Emergy, fossil fuels, unit emergy values, transformity

1. INTRODUCTION

Human society depends on fossil fuels and will likely continue so for many decades to come, in spite of our concerns for climate change, peak oil, increasing prices, and national security. We are well aware of the importance of fossil fuels and as a consequence need to assign an energetic and environmental value that is commensurate with their quality. That different energies have different qualities and thus have different costs of production and abilities to do work is a major conceptual principle of the Emergy Synthesis methodology (Odum, 1988; Odum, 1996; Brown and Ulgiati, 1997; Brown and Ulgiati, 2004). This principle is the foundation of the concept of transformity and specific emergy. Transformity (in units of seJ/J) and specific emergy (in units of seJ/g) are examples of the more general term, Unit Emergy Value (UEVs), which is defined as the ratio of available emergy of one type (emergy) that is required directly or indirectly to produce a unit output from a process. UEVs are ratios that allow the conversion of different forms of energy into a single form named emergy. Within the framework of Emergy Synthesis the quality of energy (and any other resource) is measured by the inputs of energy, materials and information required to make it. The unit emergy value (UEV) is a measure of those inputs when the inputs they are expressed in the same units. UEVs for the fossil fuels are extremely important as they form the basis for the calculation of most second order energies (e.g., electricity), products, and services.

Previous evaluations of the UEVs for fossil fuels were provided first by Odum (1996) and more recently by Bastianoni et al. (2005). In both instances the evaluations were based on a single case study. The present study is based on the total known conventional reserves of oil, natural gas² and coal over geological ages, and separates the production process into two separate steps driven first by biological processes and second by geothermal energy.

^{*} Corresponding author; E-mail: mtb@ufl.edu

² Unless otherwise stated, in this analysis the term oil means crude oil through out.

2. EXPERIMENTAL AND METHOD

The production of coal and petroleum occur in a like way through a biological and a geothermal phase. The biological steps differ since coal largely derives from terrestrial peat biomass and petroleum's sources are mainly marine. UEVs are therefore evaluated separately.

2.1 Coal

Two distinct processes contribute to coal formation (Figure 1). Firstly, living biomass is produced and accumulated as partially decomposed organic matter; then, it is transformed through a coalification phase. Both phases are separated in time and space, since ecological production ceases at some point and the accumulated organic matter is buried to achieve the second geothermal phase. The energy driving the formation of coal is assessed in two steps, accordingly. We evaluated the coal resource based on geologic age and also divided it into hard coal (anthracite/bituminous, 53% of total resource) and soft coal (sub-bituminous/lignite, 47%) based on data from the Energy Information Administration (EIA, 2010). Table 1 lists the quantity and available energy of hard and soft coal by geologic age.

Table 1. Quantity and available energy of coal by geologic period of production

Period	% of Resource ¹ Coal	Quantity ² (E9 MT)		Available Energy ³ (E18 J)	
		Anthracite & Bituminous	Sub	Anthracite & Bituminous	Sub-bituminous & Lignite
Devonian	0.1%	0.5	0.4	11.5	7.7
Carbonifer	24.3%	116.9	103	2806.4	1866.8
Permian	31.7%	152.5	135	3661.0	2435.3
Triassic	0.4%	1.9	1.7	46.2	30.7
Jurassic	16.8%	80.8	71.	1940.2	1290.6
Cretaceous	13.3%	64.0	56.	1536.0	1021.8
Tertiary	13.5%	65.0	57.	1559.1	1037.1
TOTAL	100%	481.7	427	11560.3	7690.1

Notes: (1) Data are from Bois et al. (1982) and Bestougeff (1980) as reported by Veizer et al. (1989); Walker (2000). (2) Total quantity of hard and soft coal from EIA (2010) Table 8 p.50. (3) Available energy computed using the following: Available energy in hard coal = 2.4 E10J/kg; Available energy in soft coal = 1.8 E10 J/kg

The low coal productivity in Devonian period is likely due to incomplete land colonization by organisms and therefore insufficient amount of terrestrial peat-forming biomass; the low productivity in the Triassic can be due to the well known "coal gap", the extinction of peat-forming plants at the end of Permian (Retallack et al., 1996; Beerling, 2002).

2.1.1 Phase 1: Net Primary Production to Peat

It is generally accepted that coal was formed from terrestrial sources, largely in prehistoric swamps (Teichmuller & Teichmuller, 1986). The anoxic and acidic environment of wetland soils resulted in relatively slow decomposition of organic matter leading to its accumulation in large peat deposits. Present accumulation rates of peat in swamps average about 2.5 mm/yr. In geologic ages accumulation may well have been higher. Rather than trying to estimate accumulation rates, in this analysis, we use estimates from the literature of the coal resource that was produced in each geologic age and back calculate the Net Primary Production (NPP) that was required, using the preservation factors (PFs) or efficiencies of conversion.

A preservation factor (Dukes, 2003) is the fraction of carbon that remains at the end of a transition from one fossil fuel precursor to the next, e.g. the fraction passed from plant

matter to peat, on the path to coal formation. Figure 1 shows two stages of coal formation where PFs were applied (PF1, PF2a, and PF2b). The preservation factors used in calculating NPP requirement for hard and soft coal were based on literature values and are given in Table 2.

Table 2. Preservation factors for hard and soft coal¹

Coal Type	Percent carbon ²	PF ₁ Preservation of NPP to peat ³	PF ₂ Preservation of peat to coal ³
Anthracite/Bituminou	90%	7% (+/-1.05%)	69% (+/- 17.25%)
Sub-	70%	7% (+/-1.05%)	95.6% (- 24%)

Notes: (1) Numbers in parentheses are the variation programmed in the Monte Carlo simulation. (2) Ward, 1984. (3) Dukes (2003), Tissot and Welte (1984)

The first PF is the percent of organic matter that is preserved as peat. Dukes (2003), Tissot and Welte (1984) and Frolking et al (2010) suggested values from 4% to 39%, in different situations. In our analysis we use 7% as a reasonable estimate extracted from these sources.

The emergy required for NPP was derived from literature sources related to the global NPP in each age and assuming a 15.2 E24 seJ/yr constant global emergy driving Earth processes (Brown and Ulgiati, 2010). Table 3 lists geologic ages, estimated NPPs, and calculated UEVs.

Table 3. Unit Emergy Values for NPP by geologic age (Coal)

Geologic Age	Terrestrial NPP ¹ (gC/Ma)	Specific Emergy ² (seJ/gC)	Transformity ³ (seJ/J)
Devonian	4.50E+22	9.80E+07	2.34E+03
Carboniferous	4.23E+22	1.04E+08	2.49E+03
Permian	5.40E+22	8.16E+07	1.95E+03
Triassic	5.40E+22	8.16E+07	1.95E+03
Jurassic	1.60E+23	2.76E+07	6.58E+02
Cretaceous	1.39E+23	3.17E+07	7.57E+02
Tertiary	1.32E+23	3.34E+07	7.98E+02

Notes: (1) Estimates of NPP using mass balance analysis of the stable isotopes (¹⁸O/¹⁶O) (Beerling, 1999) and Beerling et al., 1999). NPP for each age was allocated based on weighted average of values from Beerling since geologic ages were overlapping. (2) Specific emergy = emergy divided by the quantity of carbon in NPP. Emergy = 1E6 yrs * 1.52 E25 seJ/yr (total emergy driving geobiosphere) * 29% (percent of global emergy driving terrestrial production) = 4.4 E30 seJ/Ma. (3) Conversion of gC to Joules is based on 10 kcal.gC (Platt and Erwin, 1973) and 4187 J/kcal as follows: Transformity = specific emergy divided by (10 kcal/gC * 4187 J/kcal) .

The Specific Emergy of NPP ranges from 0.89 E7 to 3.55 E7 seJ/gC. NPPs and UEVs for Devonian and Triassic are not much different than for the other ages; their low coal production was therefore not due to insufficient amount of biomass, but instead more likely to unsuitable characteristics and (for Triassic) early extinction of peatforming plants.

2.1.2 Phase 2: Coalification

The peat, buried and compressed by sediments (diagenesis) slowly releases water and minor gases resulting in an increasingly compact and carbon rich substance. Coalification proceeds through several different stages, first forming lignite, then sub-bituminous coal, bituminous coal and finally anthracite. Peat organic substances that are converted to coal are sensitive to heat exposure. They are coalified with increasing depth of burial due to the increasing rock temperature with depth. The degree of coalification or coal "rank" depends more on the maximum temperatures achieved than on heating time (Teichmuller & Teichmuller, 1986).

The fraction of peat carbon that remains as coal depends on the type of coal. Dukes (2003) and Mott (1942, 1943) suggested that about 69% of the original peat carbon

remains in hard coal and 95.5% in soft coal. We used these values as preservation factors PF2a and PF2b.

Coalification is driven by geothermal processes. The geothermal energy necessary to achieve coalifications was calculated from the ratio of the mass of coal produced to the mass of the continents times annual Earth geothermal energy times the time needed for coalification (20 millions years, according to Teichmuller & Teichmuller, 1986) as follows:

Geothermal Energy used for coalification=

$$(\text{Coal mass}/\text{Continental mass}) * \text{Annual Earth Geothermal Energy} * 20\text{E}+06 \text{ yrs} \quad (1)$$

The Earth Geothermal Energy was calculated from the geothermal energy released by Earth ($4.6\text{E}+13 \text{ watt} = 1.45\text{E}+21 \text{ J/yr}$) multiplied by the Carnot efficiency at the temperatures required for coalification (approx 237.5°C for anthracite/bituminous and 97.5°C for subbituminous/lignite; Teichmuller & Teichmuller, 1986) relative to the environmental reference temperature (20°C), in order to convert energy into exergy, and finally multiplied by the transformity of geothermal exergy ($2.03\text{E}+05 \text{ seJ/J}$; Brown and Ulgiati, 2010):

$$\text{Earth Geothermal Energy} = 1.45\text{E}+21 \text{ J/yr} * 2.03\text{E}+05 \text{ seJ/J} * \text{Carnot Efficiency} \quad (2)$$

where:

Carnot efficiency at $237.5^\circ\text{C} = 0.24$; and at $97.5^\circ\text{C} = 0.08$ for coal produced in each different geologic period. Finally, we provide weighted average UEVs for both hard and soft coal.

2.2 Petroleum

Conventional crude oil reserves are usually associated with natural gas. The production of crude petroleum and natural gas is known to take place over geologic time. Similar to coal, the process can be separated into 2 distinct phases (Figure 2). The first phase is dominated by the biological production of organic matter, while geologic processes dominate the second phase. Biological carbon sources for petroleum are produced in both terrestrial and marine environments although marine sources dominate total production of reserves (87% vs 13%).

Table 4 shows the percentages of known reserves by geologic age³ and marine versus terrestrial origin (Klemme and Ulmishek, 1991). Petroleum formation on continental margins and large land-locked, isolated basins is primarily the result of algae and zooplankton productivities with additional inputs from terrestrial sources of organic matter (Tissot and Welte, 1984). Data are given as percentages in Table 4 because the calculation procedure that follows assigns energy proportional to the fraction of NPP that becomes hydrocarbons. The absolute amounts of hydrocarbons do not affect the final energy results, while percentages of total resource per age will have an effect.

³ The literature on petroleum production refers to a different system of naming geologic ages and thus the ages in Table 4 are slightly different than those used in the coal evaluation above. The coal data were given in geologic periods, while the petroleum data were given in a combination of periods and sub-periods.

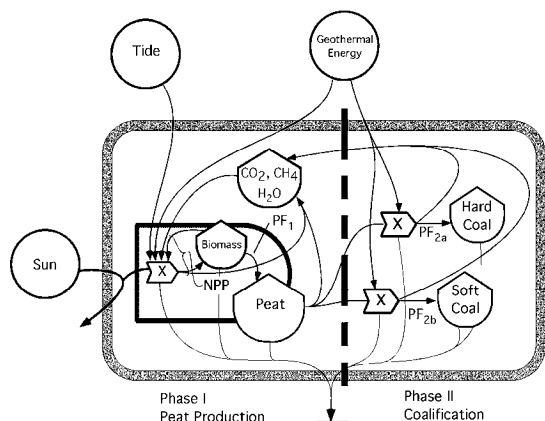


Figure 1. The two phases of coal formation. Phase I: peat production is dominated by ecological processes. Phase II: coalification is driven by geothermal energy. PF1-2 are preservation factors (fraction of carbon that is preserved and passed to the next step): PF1 is the preservation between organic matter production and peat accumulation. Hard coal and soft coal have two different preservation factors PF2a and PF2b between peat and coal.

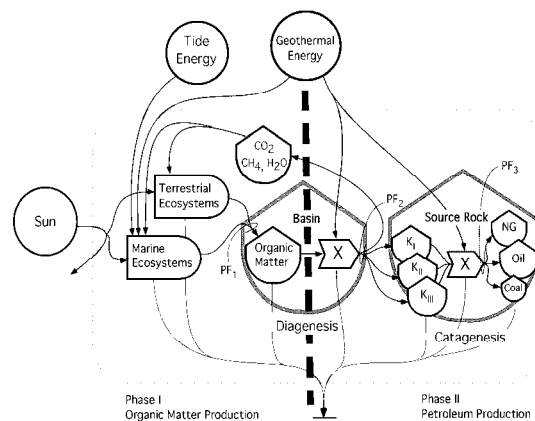


Figure 2. The two phases of petroleum formation. Phase I: organic matter production is dominated by ecological processes. Phase II: petroleum production is driven by geothermal energy. PF1-3 are preservation factors: PF1 is the preservation between organic matter production and organic matter accumulation in basins, PF2 between accumulated matter and kerogen, and PF3 between kerogen and oil/natural gas. (KI, KII, KIII = kerogen types I, II and III)

2.2.1 Phase I: Net Primary Production to Organic Sediments

In this phase of the evolution of petroleum, biological net primary production (NPP), which converts biosphere energies into organic matter is the main process. As in the coal calculation, we begin with the quantity of petroleum and natural gas that was produced in each geologic age and back calculated to the quantity of NPP that was required to produce it using preservation and conservation factors from literature. Table 5 lists the conversion factors for marine and terrestrial carbon becoming hydrocarbons (the numbers in parentheses are percent variation used in Monte Carlo simulations, below). The conversion efficiencies are based on data from Tissot and Welte (1984). The second and third columns in the table list the percent of NPP from marine and terrestrial sources that is preserved as kerogen. The fourth and fifth columns list the percent of marine and terrestrial kerogen that is converted to hydrocarbons. Tissot and Welte (1984) show that for the most part, organic matter from marine sources becomes kerogen types I and II, while terrestrial organic matter becomes kerogen type III. Conversion efficiencies of terrestrial organic matter are in general much lower than those for organic matter derived from marine NPP (Table 5).

We allocate the emergy driving the geobiosphere (sum of solar radiation, tidal momentum and geothermal energy: 15.2 E24 sej/yr) to terrestrial and marine systems based on their percent of the total surface area of the Earth (terrestrial = 30%; marine = 70%) assuming such percent to be constant over the geological ages (the large uncertainty of information over very long time periods makes this assumption reasonable). The analysis separates terrestrial and marine organic matter production since they have different productivity and UEVs (Table 6). Each geologic age has differing overall NPP as estimated by Beerling (1999) and Beerling et al. (1999) and is responsible for differing amounts of oil production (Klemme and Ulmishek, 1991). Calculating backward from the petroleum resource produced in each geologic age and using the efficiencies in Table 5 we allocated geobiosphere emergy driving NPP that becomes petroleum organic matter. Once NPP as grams carbon is known, the geobiosphere emergy is assigned to this quantity based on the UEVs given in Table 6.

Table 4. Percent of global reserves of petroleum hydrocarbons generated by geologic age

Geological Age	Geological ages (Ma, million years) before present		Percent of hydrocarbons generated*	Percent of hydrocarbons generated per kerogen type			
				From kerogen types I & II (mainly marine)		From kerogen type III (mainly terrestrial)	
	From	To		Oil	Natural Gas	Oil	Natural Gas
Silurian	438	408	9.0%	15%	85%	=	=
Upper Devonian- Turonian	374	352	8.0%	80%	20%	=	=
Pennsylvanian -Lower Permian	320	286	8.0%	35%	43%	=	22%
Upper Jurassic	169	144	25.0%	74%	26%	=	=
Middle Cretaceous	119	88.5	29.0%	61%	10%	4%	25%
Oligocene-Miocene	36.6	5.3	12.5%	28%	7%	39%	26%

(*) Percentages do not add up to 100% due to lower productivity periods not included in this account.

Table 5. Efficiencies of conversion of biomass to kerogen and from kerogen to hydrocarbons¹

Time Period	Marine biomass conversion to kerogen ¹ .	Terrestrial biomass conversion to kerogen ¹ .	Marine kerogen conversion to hydrocarbons ² .	Terrestrial kerogen conversion to hydrocarbons ² .
All Geologic Ages	4% (+/- 1%)	2% (+/- 0.5%)	75% (+/- 15%)	20% (+/- 5%)

Notes: (1) Numbers in parentheses are the variation programmed in the Monte Carlo simulation. (2) Conversion efficiencies are from Demaison and Murris (1984). (3) Conversion efficiencies are from (Klemme and Ulmishek, 1991) and hydrocarbons/kerogen ratios from Behar et al. (1997), Tissot et al. (1987), Kenneth et al. (1994), Waples (1994), and Klemme (1994).

Table 6. Net primary production, total energy, and Unit Energy Values of NPP by geologic age (oil and natural gas).

Geological Age	Marine NPP (g C) ¹	Terrestrial NPP (g C) ¹	Total energy driving marine NPP ² (seJ)	Total energy driving terrestrial NPP ² (seJ)	UEV of Marine NPP ³ (seJ/gC)	UEV of Terrestrial NPP ³ (seJ/gC)
Silurian	1.23E+24	1.43E+24	3.19E+32	1.37E+32	2.61E+08	9.59E+07
Upper Devonian-Turonian	4.23E+23	9.30E+23	2.34E+32	1.00E+32	5.54E+08	1.08E+08
Pennsylvanian -Lower Permian	1.38E+24	1.52E+24	3.62E+32	1.55E+32	2.62E+08	1.02E+08
Upper Jurassic	3.66E+24	4.03E+24	2.66E+32	1.14E+32	7.27E+07	2.83E+07
Middle Cretaceous	3.31E+24	3.79E+24	3.25E+32	1.39E+32	9.81E+07	3.67E+07
Oligocene-Miocene	2.58E+24	3.12E+24	3.33E+32	1.43E+32	1.29E+08	4.58E+07

Notes: (1) NPP estimates according to Beerling (1999) and Beerling et al. (1999). (2) Calculated as the time per geologic age times the geobiosphere energy flow (15.2E24 seJ/yr) times 29% for terrestrial and 71% for marine recognizing the split between terrestrial and marine systems. (3) Energy in columns 4 and 5 divided by the NPP in columns 2 and 3.

2.2.2 Phase II: Petroleum Generation

The three main geologic stages of the evolution of organic matter in sediments (diagenesis, catagenesis, and methanogenesis) are geologic processes driven by geothermal processes.

During diagenesis, the temperature increases are small and CO₂ and water are released. The main form of carbon is organic carbon. During catagenesis the temperature

increases reaching between 50 °C and 150 °C. The main carbon form is hydrocarbons, as this stage is the principle stage of crude oil formation (early) followed by wet gas in the latter stages. The methanogenesis stage results in only the production of dry gas at higher temperatures (up to 200°C); thus the main carbon form is methane. During the geologic stages of petroleum formation, time and temperature are important, although Tissot and Welte (1984) suggest that transformation is more influenced by temperature than by time. We allocate geothermal energy to catagenesis and methanogenesis processes based on the time and temperature. In a study of petroleum basins in Wyoming, the USGS (2005) estimated average times and temperatures for oil and gas formation, confirming previously published research. They estimated 20 million years at between 50 °C and 150 °C for oil generation during catagenesis and further 12 million years at between 150 °C and 200 °C for gas generation during methanogenesis, respectively. Tissot and Welte (1984) also reported temperatures for significant generation of oil as between 50 °C and 150 °C. We used 100 °C for catagenesis and 175 °C for methanogenesis. The geothermal available energy necessary to achieve catagenesis and methanogenesis was based on the ratio of the mass of oil and natural gas produced to the mass of the continents multiplied by the annual geothermal available energy times the time for each (20 millions years for catagenesis and 12 million years for methanogenesis) and using Equations 1 and 2 above. The geothermal available energy was calculated using Carnot efficiencies of 21% for 100 °C and 34% for 175 °C.

3. RESULTS AND DISCUSSION

3.1 Monte Carlo Simulation of UEVs for Coal, Oil, and Natural Gas

There are obvious uncertainties in the data used to calculate the energy required for each phase of production of fossil fuels. Taking these uncertainties into consideration, we developed Monte Carlo simulations for coal as well as for petroleum oil and natural gas. We allowed each of the preservation factors, conversion efficiencies, and the NPP UEVs for geologic ages to vary by predetermined amounts depending on the range of values found in the literature for each variable. In the coal simulation, peat preservation values (PF1) were programmed to vary between +/- 15% and coal preservation (PF2) varied +/- 25% but the sub-bituminous / lignite PF was constrained below 95.6% assuming that the reported value was near the maximum preservation factor. The UEVs of NPP were programmed to vary between +/- 25% from values listed in Tables 3. In petroleum and natural gas simulations, conversion efficiencies (Table 5) were programmed to vary +/-25%. UEV values of NPP (Table 6) were also programmed to vary +/- 25%. Each simulation was allowed to run for 1000 iterations with variables programmed to vary randomly between minimum and maximum values. We report mean values per geologic age and a weighted mean for each fossil fuel type based on percent of total reserve in each age. Results are shown in Figures 3 and 4. Tables 7 and 8 list mean UEVs for coal and oil/natural gas, respectively, by geologic age. Mean values for each age are representative of the work of the biosphere to generate the fossil fuels and were computed as the mean of the values obtained from the Monte Carlo simulation. The weighted mean was computed based on the percent of resource produced in each geologic age. These UEVs are appropriate values to use when evaluating the inputs of raw resources to the global economy.

Figure 3. Results of the Monte Carlo simulation for the transformity of anthracite and bituminous coal (top) and sub-bituminous & lignite coal (bottom). The gray bands on either side of the mean represent one standard deviation about the mean.

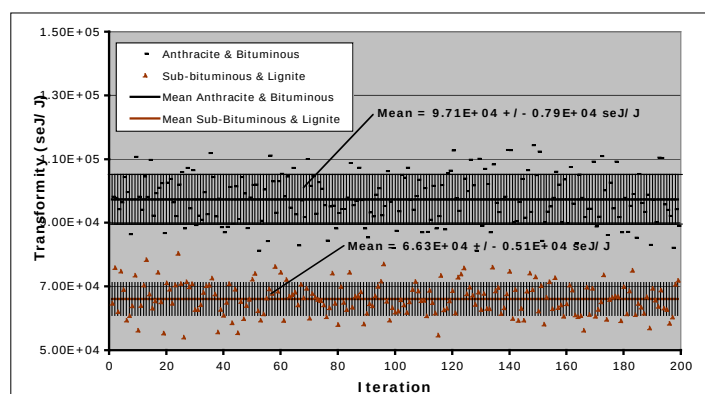
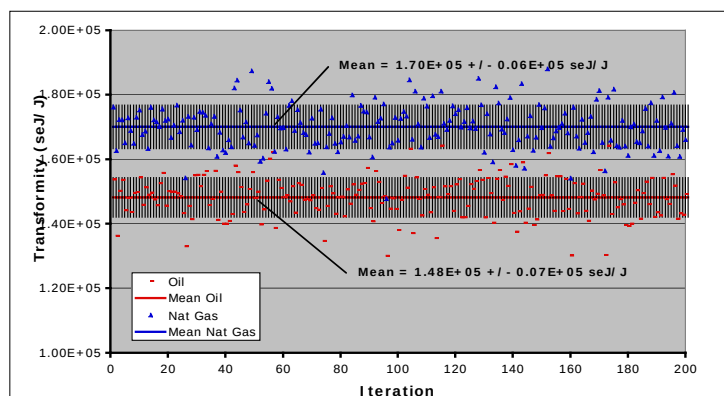


Figure 4. Results of the Monte Carlo simulation for the transformity of Natural Gas (top) and crude oil (bottom). The gray bands on either side of the mean represent one standard deviation about the mean.



Coal mining and oil well production is energy intensive and adds to the transformity of fossil fuels as they approach their end use. They are not appropriate UEVs to use when evaluating inputs to economic processes where, in reality, the inputs are refined fuels such as gasoline, residual oil (heavy fuel oil) or diesel fuel or coal that has been mined and transported. In a companion paper (Brown et al, 2010) we also calculate the values for imported and refined fuels by taking into proper account further transport and industrial costs.

Table 7. Mean UEVs for coal by geologic age¹

Geologic Age	Transformities of Anthracite & Bituminous (seJ/J)	Transformities of Sub-bituminous & Lignite (seJ/J)
Devonian	9.35E+04	5.79E+04
Carboniferous	9.73E+04	6.42E+04
Permian	7.79E+04	5.02E+04
Triassic	7.88E+04	5.09E+04
Jurassic	2.45E+05	1.68E+05
Cretaceous	3.73E+04	2.13E+04
Tertiary	3.85E+04	2.21E+04
Weighted Mean²	9.71E+04	6.63E+04

Notes: (1) Mean values are based on 1000 iterations of the Monte Carlo simulation. (2) Weighted mean is based on percent of coal resource in each geologic age

While the UEVs computed in each geologic age are sensitive to the overall productivity (NPP) of that age, it is important to note that the global quantity of coal, oil, or natural gas does not influence their overall UEV. So, while we have used best estimates of the global reserves of these fossil energies that are available, changes in the known reserves will not affect the UEVs calculated. A better understanding of the processes of diagenesis, catagenesis and methanogenesis as well as the preservation factors from organic matter to kerogen would sharpen the analysis and more than likely reduce the standard deviation of our simulation results, but would not substantially alter the final UEVs calculated.

Table 8. Mean UEVs for marine and terrestrial crude oil and natural gas by geologic age¹

Geologic Age	Transformities of marine oil (seJ/J)	Transformities of marine nat gas (seJ/J)	Transformities of terrestrial oil (seJ/J)	Transformities of terrestrial nat gas (seJ/J)
Silurian	2.10E+05	1.70E+05		
Upper Devonian-Touronian	4.50E+05	3.64E+05		
Pennsylvanian -Lower Permian	2.18E+05	1.77E+05		5.08E+05
Upper Jurassic	6.28E+04	5.11E+04		
Middle Cretaceous	8.41E+04	6.83E+04	2.34E+05	1.90E+05
Oligocene-Miocene	1.16E+05	9.41E+04	3.00E+05	2.43E+05
Weighted mean²	1.39E+05	1.37E+05	2.76E+05	2.38E+05

Notes: (1) The mean is the result of 1000 Monte Carlo iterations. (2) Weighted mean is based on percent of oil or natural gas resource in each geologic age

This analysis represents a major departure from previous evaluations of fossil fuels as our results suggest that they are significantly more valuable (higher transformities) than previously computed UEVs would support. Since fossil fuels are primary drivers of economic processes, such UEV changes will require much recalculation of standard UEVs of many secondary products and processes. It would be convenient if a simple ratio could be used to transform UEVs of products and processes that were calculated using earlier fossil fuel UEVs, but unfortunately since every process and product contains differing amounts of fossil energies in relation to other inputs, there is no simple solution.

We have computed UEVs for fossil resources and fuels without services. UEVs without services are based solely on the emergy content and the emergy costs of production, transportation, and refining. Labor is not included. A UEV with services can easily be computed at any stage of the energy supply chain by multiplying the average price of each resource or fuel type by the emergy-to-money ratio for the economy of interest.

4. CONCLUSION

A major criticism of the emergy synthesis methodology in the past has been that a single transformity for oil or coal, for example, was applied worldwide despite the fact that it is well known that fossil fuels have been developed under wide ranging conditions at very different time scales, and thus a single transformity is an over simplification. There was no question in our minds that this critique was accurate and it has taken a number of years to assemble the data (and the time) to re-evaluate these previous attempts of computing fossil energy transformities. We have therefore carefully computed UEVs for the fossil fuels based on geologic process and time scales. We have strengthened our evaluation by taking into consideration the uncertainties that exist in the general understanding of coal and petroleum genesis through Monte Carlo simulations that incorporate uncertainty and nonlinearity of the interactions of time, temperature, biology and geology. We provide new mean UEVs of the coal resource over the entire geologic past range between 6.63 E4 (+/-0.51 E4) seJ/J and 9.71 E4 (+/-0.79 E4) seJ/J. Oil and natural gas resource UEVs have mean values of 1.48 E5 (+/- 0.07 E5) seJ/J and 1.71 E5 (+/- 0.06 E5) seJ/J respectively. These UEVs quantify the effort of the geobiosphere in producing these resources and through such quantification provide a complementary point of view to the usual economic value.

REFERENCES

- Bastianoni, S, D. Campbell, L. Susani and E. Tiezzi, 2005. "The solar transformity of oil and petroleum natural gas". *Ecological Modelling* 186, Nr. 2: 212-220. doi:10.1016/j.ecolmodel.2005.01.015

- Beerling, D.J. 1999, "Quantitative estimates of change in marine and terrestrial primary productivity over the past 300 million years". *Proceedings: Biological Sciences, Royal Society, London*. Vol. 266;1821-1827.
- Beerling, D.J. 2002. "CO₂ and the end-Triassic mass extinction". *Nature*. Vol 415:386-87.
- Beerling, D.J., F.I. Woodward, and P.J. Valdes, 1999. "Global terrestrial productivity in the mid-Cretaceous (100 Ma): Model simulations and data". in Barrera, E. and C.C. Johnson (eds). *Evolution of the Cretaceous ocean-climate system, Geological Society of America, Special Papers*, 332, p. 385-390
- Behar, F. M. Vandenbroucke, Y. Tang, F. Marquis and J. Espitalie 1997. "Thermal cracking of kerogen in open and close systems: determination of kinetic parameters and stoichiometric coefficients for oil and gas generation". *Organic Geochemistry*. Vol. 26, No. 5/6, pp.312-339
- Bestougeff, M.A. 1980. "Summary of mondial coal resources and reserves: Geographic and geologic repartition". *Revue Inst. Francais Petrole*, V.35, p.353-366.
- Bois, C. Bouche, P. and Pelet, R. 1982. "Global geologic history and distribution of hydrocarbon reserves". *Am. Assoc. Petroleum Geologists Bull.*, v.66, p.1248-1270.
- Brown, M.T. and S. Ulgiati. 1997. "Emergy Based Indices and Ratios to Evaluate Sustainability: Monitoring technology and economies toward environmentally sound innovation". *Ecological Engineering* 9:51-69
- Brown, M.T. and S. Ulgiati. 2004. "Emergy and environmental accounting". In C. Cleveland. (ed) *Encyclopedia of Energy*. Elsevier. New York
- Brown, M.T., Ulgiati, S., 2010. "Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline". *Ecological Modelling*, 221(20): 2501-2508
- Demaison, G., and Murris, R. J.eds., 1984. "Petroleum Geochemistry and Basin Evaluation". *AAPG Memoir* 35.
- Dukes, J. S., 2003. "Burning Buried Sunshine: Human Consumption Of Ancient Solar Energy". *Climatic Change*, 61, 31-44.
- EIA, 2010. *U.S. Coal Consumption by End Use Sector, by Census Division and State*. US Energy Information Agency. Downloaded on 21July, 2010 from <http://www.eia.doe.gov/cneaf/coal/page/acr/table26.html>.
- Frolking, S., Roulet, N.T., Tuittila, E., Bubier, J.L., Quillet, A., Talbot, J., and Richard, P. J. H., 2010. "A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation". *Earth Syst. Dynam. Discuss.*, 1: 115–167. www.earthsystem-dynam-discuss.net/1/115/2010/doi:10.5194/esdd-1-115-2010
- Kenneth et al., 1994. "Applied source rock geochemistry". In: *The petroleum system - from source to trap* (Edited by L. B. Magoon and W.G. Dow). *AAPG Memoir* 60, pp. 93-121.
- Klemme, H.D. 1994. "Petroleum system of the world involving upper Jurassic source rocks". In Magoon, L. B, and W. G. Dow (eds.), *The petroleum system—from source to trap: Am. Assoc. Petroleum Geologists Special Volumes M* 60: 93-121
- Klemme, H.D. and G. F. Ulmishek, 1991. "Effective Petroleum Source Rocks of the World: Stratigraphic Distribution and Controlling Depositional Factors". *AAPG Bulletin* vol. 75, No. 12: 1809-1851.
- Mott, R. A.: 1942, "The Origin and Composition of Coals". *Fuel in Science and Practice* 21, 129–135.
- Mott, R. A.: 1943, "The Origin and Composition of Coals". *Fuel in Science and Practice* 22, 20–26.
- Odum, H.T. 1988. "Self organization, transformity, and information". *Science* 242(Nov. 25, 1988): 1132-1139.
- Odum, H.T. 1996. *Environmental Accounting: Emergy and environmental decision making*. John Wiley & Sons, New York 370p.
- Platt, T. and B. Erwin, 1973. "Caloric content of phytoplankton". *Limnology and Oceanography*.18: 306-309
- Retallack, J.G., Veevers, J.J., and Morante, R., 1996. "Global coal gap between Permian-Triassic extinction and Middle Triassic recovery of peat-forming plants". *Geologic Society of American Bulletin*, 108(2): 195-207.
- Teichmuller, R. and M. Teichmuller. 1986. "Relations Between Coalification and Palaeogeothermics" In Variscan And Alpidic Foredeeps Of Western Europe. *Paleogeothermics* 5: 53–78. <http://www.springerlink.com/index/W2V4216P7U36H4Q1.pdf>.
- Tissot B.P., R. Pelet, and P. Ungerer. 1987. "Thermal history of sedimentary basins, maturation indices, and kinetics of oil and gas generation". *Am. Assoc. Petroleum Geologists Bulletin* 71:12, p. 1445-1466.

- Tissot, B.P and D.H. Welte. 1984. *Petroleum Formation and Occurrence*. Springer-Verlag. New York. 699p.
- Veizer, J., P. Laznicka, and S.L. Jansen. 1989. "Mineralization through geologic time: recycling perspective". *American Journal of Science* 289:4. Pp 484-524
- Walker, S., 2000. *Major Coalfields of the World*. IEA Coal Research, London. pp.131.
- Waples, D. W. 1994. "Maturity modeling: thermal indicators, hydrocarbon generation, and oil cracking". in Magoon, L. B, and W. G. Dow (eds.), *The petroleum system—from source to trap*: Am. Assoc. Petroleum Geologists Special Volumes M 60:285-306.
- Ward, C., 1984. *Coal Geology and Coal Technology* Blackwell Scientific Press, 1984

EMERGY EVALUATION OF AVOCADO CROP AS RAW MATERIAL FOR BIODIESEL PRODUCTION

Fábio Takahashi¹ and Enrique Ortega²

State University of Campinas - UNICAMP

ABSTRACT

The production of biodiesel in Brazil has increased significantly in recent years. The main raw materials used to produce biodiesel are soybean oil (84%), bovine fat (13%) and other fatty materials (3%). The use of avocado oil for biodiesel production is, nowadays, under research. Oil can be extracted from the avocado pulp and ethyl alcohol can be obtained from the fruit pit, which is an input used in the production of biodiesel. Avocado can be cultivated throughout all the Brazilian territory, even in the steep terrains where the farming of another oleaginous crop is hard to carry on. The aim of this paper is to evaluate the avocado crops cultivated in Brazil using the emergy methodology and to compare the results with other oleaginous crops emergy indicators in order to determine which crop is the most sustainable. This study evaluates two conventional agro-chemical models. The renewability index (%R) range from 32% to 44% depending on the type of management adopted. These results show a high renewability index when compared to another oleaginous crop: rapeseed (40%), sunflower (31%), soybeans (30%), oil palm (28%) and cotton (17%). Thus, it is indicated that avocado can be used as a raw material for biodiesel production with, at least, the same environmental impact of the other oleaginous crops and, moreover, it could contribute to the Brazilian energy matrix.

Keywords: biodiesel, avocado, emergy synthesis

1. INTRODUCTION

Brazil is already a biofuels producer country, with a great potential for further production of ethanol and biodiesel. The Brazilian National Program for Production and Use of Biodiesel (PNPB) was launched in December 2004. Besides the economic objective of fostering biodiesel production, a major social objective was the regional development via promotion of small agricultural units family managed. The PNPB provides research incentives for projects associated with biodiesel and it stimulated the market demand for biodiesel in the Brazilian energy matrix (Pousa et al., 2007). The production of biodiesel in Brazil has increased in recent years as well as much research was done on biodiesel in order to develop new technologies. The use of avocado oil to produce biodiesel is one of these studies. The biodiesel productive chain during the agricultural stage incorporates renewable energy (solar radiation, rain, soil nutrients). Thus, the evaluation of agricultural stage is crucial to verify the sustainability of the final product. The emergy evaluation of the main raw materials for biodiesel production was studied in a previous work (Takahashi and Ortega, 2010) and the aim of this study is to assess the avocado and to compare the results with the other raw materials.

1.1. Biodiesel

Biodiesel is a fuel produced from vegetable oils, animal fats and recycled cooking oil. It is defined by PNPB as a "biofuel derived from renewable biomass for use in engines of internal combustion with ignition by compression or for generation of another type of

¹ fabiotak@gmail.com

² ortega@fea.unicamp.br tel. +55 19 35214035

energy that can partially or totally substitute fossil fuels” (Pousa et al., 2007). PNPB stimulated the market demand for biodiesel in the Brazilian energy matrix encouraging the optional use of B2 (a diesel fuel with the addition of 2% of biodiesel) until the beginning of 2008. Biodiesel blends in diesel were set according to Table 1.

Table 1. Blends of biodiesel that have been used in Brazil since 2008 (ANP, 2010).

Period	Blend
January 2008 – June 2008	2%
July 2008 – June 2009	3%
July 2009 – December 2009	4%
January 2010	5%

The world-wide production of biodiesel increased by 200% from 1995 to 2006; the European Union alone was responsible for 75% of the global production of biodiesel in 2006 (Demirbas et al., 2009). Brazil has a total of 63 biodiesel industrial units with an annual capacity of 14.174 m³/day. As shown in Fig. 1, Brazilian biodiesel production has grown fast in recent years, the main raw materials used are soybean (84%) and bovine fat (13%).

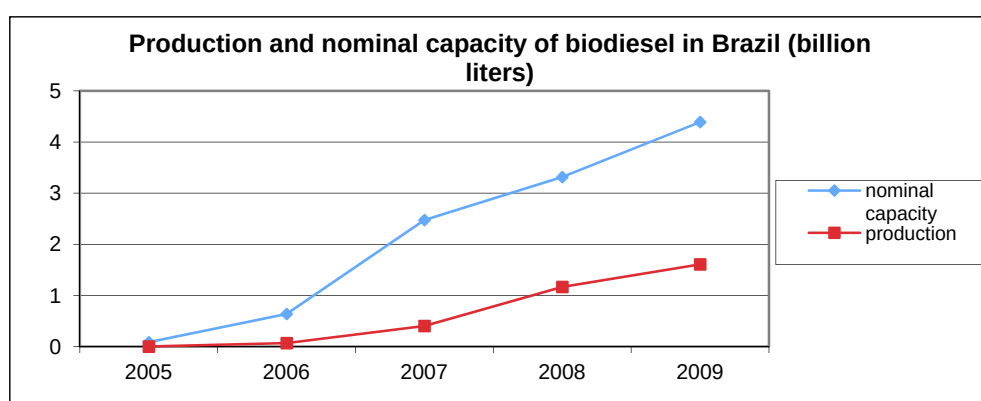


Figure 1. Production and nominal capacity of biodiesel in Brazil.

Recent research studied the avocado oil biodiesel production. Avocado can be cultivated throughout all the Brazilian territory, even in the steep terrains where the farming of another oleaginous crop is difficult. Avocado biodiesel shows similar characteristics to soybean biodiesel, especially kinematic viscosity, carbon leached ashes residue, fluidity and freezing point. Furthermore, the use of this raw material is advantageous because ethanol can be obtained from the avocado pit (Meneses et. al, 2009).

2- MATERIALS AND METHOD

2.1 Emergy synthesis

Fundamentals of emergy synthesis can be found in the book Environmental Accounting (Odum, 1996). Emergy is defined as the sum of all inputs of energy directly or indirectly required in the process of producing a given product and it is expressed in solar equivalent Joules (seJ) (Scienceman, 1987, Odum, 1988). Emergy synthesis considers inputs from nature (e.g. sun, rain, wind, soil nutrients) and from the economy (e.g., goods, services, machinery, fossil fuels). It is a powerful tool that can measure the real wealth of the nature and society work and assess public policies aimed at sustainability and fair trade (Odum, 1996; Brandt-Williams, 2002, Ultiati and Brown, 1998).

Emergy methodology can be used to evaluate agricultural systems with different types of management and production and, thus, to evaluate which is the most sustainable

(Ortega et. al., 2005; Martin et al., 2006, La Rosa et al., 2008, Brandt Williams, 2002; Takahashi and Ortega, 2010).

The first step in an emergy diagnosis is to construct the diagram that identifies all inputs, outputs, components and their relationships. The next step is to measure the system inputs and outputs. Every inputs must be multiplied by a conversion factor (Unit Emery Value, UEV), so that, they can be expressed in solar equivalent Joules. Transformity is defined as the emery input per unit of available energy (exergy) output. For example, if 4000 seJ are required to generate a Joule of wood, then the solar transformity of that wood is 4000 seJ per Joule (or seJ/J) (Brown and Ulgiati, 2004b). Then the flows or emery can be aggregated according to their origin, as shown in Table 2, by considering the renewability fraction of each material and service (Ortega et al., 2005; Ulgiati et al., 1994; Agostinho et al., 2008). The renewability fraction is that fraction of energy from some materials and services that can be considered as renewable, such as seedling, seeds, manure and labor. The last step includes a calculation and evaluation of the emery indices as shown in Table 3.

Table 2. Emery-aggregated flows.

Inputs classification	Equation / Symbol	Description
Renewable resources from nature	R	Sun, rain, wind.
Non-Renewable resources from nature	N	Soil, biodiversity, people exclusion.
Resources from Nature	$I = R + N$	
Materials	$M = M_R + M_N$	
Renewable Materials	M_R	Seeds, wood.
Non-renewable Materials	M_N	Fuels, chemicals.
Services	$S = S_R + S_N$	
Renewable Services	S_R	Manpower supported by renewable sources.
Non-renewable Services	S_N	Services such as external services, taxes, insurance.
Feedback from economy	$F = M + S$	
Total Emery	$Y = I + F$	

2.2. Data collection for the emery evaluation

Data for emery evaluation were obtained from AGRIANUAL (Agrianual, 2006), which is an important publication that provides data of the productivity and profitability of agricultural products in Brazil. Data from two avocado production systems in São Paulo and Minas Gerais states were used in this study and the results were compared with the results of other oleaginous crops (Takahashi and Ortega, 2010).

3. RESULTS AND DISCUSSION

Figure 2 shows a simplified diagram of avocado production and Tables 4 and 5 show the emery flow for the avocado system located in Minas Gerais state and São Paulo state respectively (See references in APENDIX 1). These tables show the emery flow of each input, the total emery flow, the emery produced and the money received due to the sales.

Table 3. Emery indicators.

Indicator	Expression	Concept
Total Emery (Y)	$Y = I + F$	Total Emery
Emery of product (E)	$E = \text{caloric value of product}$	Emery

Transformity (Tr)	$Tr = Y / E$	Total Emergy / Energy
Renewability (%R)	$\%R = 100 \times (R+M_R+S_R)/Y$	Renewable inputs / Total emergy
Emergy Yield Ratio (EYR)	$EYR = Y / F$	Total Emergy / Emergy from economy
Emergy Investment Ratio (EIR)	$EIR = F / I$	Emergy from economy/ Emergy from Nature
Environmental Loading Ratio (ELR)	$ELR = (M_N+S_N + N)/ (R+M_R+S_R)$	Non-Renewable / Renewable
Emergy Exchange Ratio (EER)	$EER = Y / [(\$) \times (seJ/\$)]$	Total emergy / emergy received from the buyer
Renewable Mobilization	Benefit = R/F	Renewable from Nature / Emergy from economy

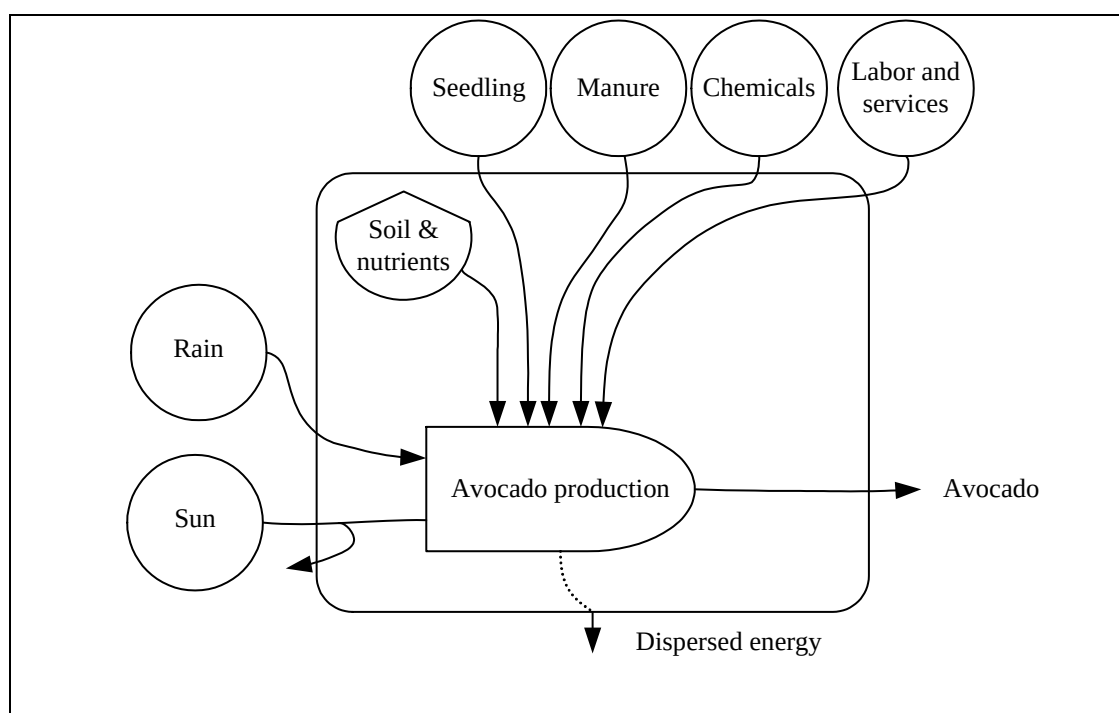


Figure 2. Diagram of an avocado system.

Table 6 shows the emergy aggregated flow and its notable the great difference between the material from economy flows. The system located in São Paulo State uses almost 3 times more emergy from material and 45% of this emergy is renewable from the use of manure. The difference of the total emergy used by both systems is also due to the use of manure, whereas the other aggregated flows are similar. This difference increases the %Renewability of São Paulo system but also reduce its transformity as shown in Table 7.

Table 4. Emergy flows for avocado system in Minas Gerais state.

Code	Item	Renew. fraction	Quantity	Unit	Transformity (seJ/unit)	Renew. Emergy Flow	Non-Renew. emergy Flow	Total emergy Flow
						E12 seJ/ha/y r	E12 seJ/ha/y r	E12 seJ/ha/y r
R1	Sun	1	6.65E+13	J	1	66.49	0	66.49

R3	Rain	1	8.11E+10	J	3.10E+04	2512.55	0	2512.55
N1	Net topsoil loss	0	8.06E+08	J	1.24E+05	0.00	99.94	99.94
M3	Seedling	0.20	7.80	US\$	5.02E+12	7.83	31.32	39.16
M6	Limestone	0	900.00	Kg	1.68E+12	0.00	1512.00	1512.00
M29	Manure	0.50	800.00	Kg	8.03E+12	3212.00	3212.00	6424.00
M36	Fungicide	0.	2.00	Kg	2.48E+13	0.00	49.60	49.60
M37	Insecticide	0	4.90	Kg	2.48E+13	0.00	121.52	121.52
M38	Formicide	0	3.00	Kg	2.48E+13	0.00	74.40	74.40
M40	Zinc Sulfate	0	11.97	Kg	7.20E+13	0.00	861.84	861.84
	Ammonium							
M41	Sulfate	0	59.50	Kg	3.80E+11	0.00	22.61	22.61
M50	Chemicals	0	3.68	Kg	6.38E+11	0.00	2.35	2.35
M61	NPK (00-30-15)	0	49.00	Kg	4.28E+12	0.00	209.96	209.96
M62	NPK (26-00-26)	0	560.00	Kg	2.64E+12	0.00	1478.42	1478.42
S1	Labor	0.60	131.05	US\$	5.02E+12	394.72	263.15	657.87
S2	Security	0	10.00	US\$	5.02E+12	0.00	50.20	50.20
	Technical							
S3	assistance	0	60.00	US\$	5.02E+12	0.00	301.20	301.20
	Labor –							
S4	management	0	193.40	US\$	5.02E+12	0.00	970.87	970.87
S5	Transport	0	10.00	US\$	5.02E+12	0.00	50.20	50.20
S6	Taxes	0	60.43	US\$	5.02E+12	0.00	303.36	303.36
S7	Telephone	0	90.00	US\$	5.02E+12	0.00	451.80	451.80
S8	Other costs	0	540.56	US\$	5.02E+12	0.00	2713.61	2713.61
Total emergy			1.89E16	seJ/ha/yr				
Total energy			4.54E10	J/ha/year				
Sales			2621.60	US\$/ha/year				

The transformity measures the efficiency of the system, in other words, how much of the emergy used is converted into net energy. The MG avocado system is more efficient than SP one.

The renewability index (%R) is the percentage of renewable emergy used by the system. SP avocado system uses more renewable emergy than MG avocado system, as already explained, due to the use of a high quantity of manure.

Table 5. Emergy flows for avocado system in São Paulo State.

Code	Item	Renew. fraction	Quantity	Unit (unit / ha/yr)	Transformity (seJ/unit)	Renew. Emergy Flow E12 seJ/ha/yr	Non-Renew. emergy Flow E12 seJ/ha/yr	Total emergy Flow E12 seJ/ha/yr
R1	Sun	1	6.62E13	J	1	66.23	0.00	66.23
R3	Rain	1	7.54E+10	J	3.10E+04	2337.40	0.00	2337.40
N1	Net topsoil loss	0	8.06E+08	Kg	1.24E+05	0.00	99.94	99.94
M3	Seedling	0.01	10.4	US\$	5.02E+12	10.44	41.77	52.21
M6	Limestone	0.01	900	Kg	1.68E+12	0.00	1512.00	1512.00
M29	Manure	0.5	3600	Kg	8.03E+12	14454.0	14454.0	28908.0
M35	Herbicide	0.01	2.86	Kg	2.48E+13	0.00	70.93	70.93
M36	Fungicide	0.01	3.76	Kg	2.48E+13	0.00	93.25	93.25
M37	Insecticide	0.01	2.37	Kg	2.48E+13	0.00	58.78	58.78
M38	Formicide	0.01	0.52	Kg	2.48E+13	0.00	12.90	12.90

M40	Zinc Sulfate	0.01	4.55	Kg	7.2E+13	0.00	327.60	327.60
	Ammonium							
M41	Sulfate	0.01	444.5	Kg	3.8E+11	0.00	168.91	168.91
M50	Chemicals	0.01	735.3	Kg	6.38E+11	0.00	469.12	469.12
M61	NPK (0-30-15)	0.01	49	Kg	4.28E+12	0.00	209.96	209.96
S1	Labor	0.6	248	US\$	5.02E+12	746.98	497.98	1244.96
	Technical							
S2	assistance	0	60	US\$	5.02E+12	0.00	301.20	301.20
	Labor –							
S3	management	0	193.4	US\$	5.02E+12	0.00	970.87	970.87
S4	Taxes	0	45.32	US\$	5.02E+12	0.00	227.51	227.51
S5	Telephone	0	90	US\$	5.02E+12	0.00	451.80	451.80
S6	Other costs	0	399.75	US\$	5.02E+12	0.00	2006.75	2006.75
Total energy			3.95E16	seJ/ha/year				
Total energy			4.54E10	J/ha/year				
Sales			1966.20	US\$/ha/year				

Table 6. Aggregated energy flows.

Classification of inputs	Equations	Minas Gerais (E13 sej/ha/yr)	São Paulo (E13 sej/ha/yr)
Renewable resources from nature	$R=R_1+R_2+...+R_i$	251.26	233.74
Non-renewable resources from nature	$N=N_1+N_2+...+N_i$	9.99	9.99
Emergy from nature	$I = R + N$	261.25	243.73
Materials from economy	$M=M_1+M_2+...+M_i$	1079.59	3188.36
Materials from economy (renewable)	$Mr=Mr_1+Mr_2+...+Mr_i$	321.98	1446.44
Materials from economy (non-renewable)	$Mn=Mn_1+Mn_2+...+Mn_i$	757.60	1741.92
Services from economy	$S=S_1+S_2+...+S_i$	549.91	520.31
Services from economy (renewable)	$Sr=Sr_1+Sr_2+...+Sr_i$	39.47	74.70
Services from economy (non-renewable)	$Sn=Sn_1+Sn_2+...+Sn_i$	510.44	445.61
Feedback from economy	$F = M + S$	1629.50	3708.67
Total emergy	$Y= I + F$	1890.75	3952.41

The emergy yield ratio (EYR) is the ratio between total emergy and emergy value of economy purchased inputs. This ratio measures the ability of a process to exploit and make local sources available by investing in outside resources, in other words, it is the measure of the use of local resources. Both systems show small EYR values, indicating the high dependency of resources from economy. Values of EYR closer of 1 indicate a lower net emergy of the system.

Table 7. Emergy indicators.

Indicators	Avocado MG	Avocado SP
Transformity (sej/J)	4.16E+05	8.70E+05
Renewability	32%	44%
Emergy Yield Ratio (EYR)	1.16	1.07
Emergy Investment Ratio (EIR)	6.24	15.22
Emergy Exchange Ratio (EER)	1.44	4.00
Emergy Loading Ratio (ELR)	2.09	1.25
R/F	0.15	0.01

The emergy investment ratio (EIR) measures the intensity of use of economic resources. This indicator shows that the MG avocado is less dependent of resources from economy than the SP avocado.

The emergy exchange ratio (EER) would have a value of 1 to represent that all emergy spent to produce the product is returned to the producer by the money received. The MG avocado shows better results because the value is lower and close to 1.

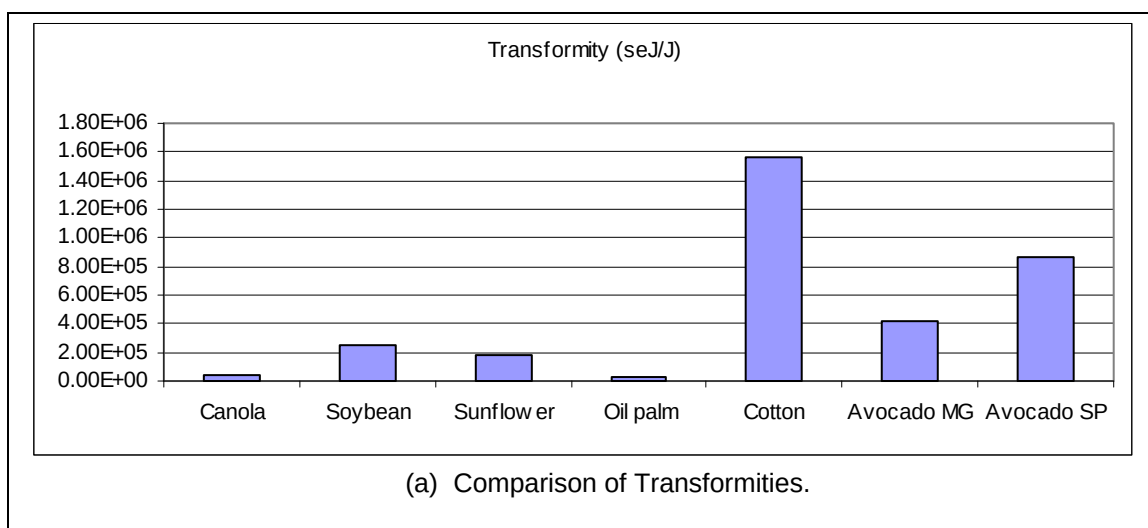
The emergy loading ratio (ELR) is an indicator of the pressure of the system on the environment and may be considered a signal of possible ecosystem stress. The lower value of this indices show that SP avocado has a lower pressure on the environment.

The indicator R/F shows the ratio between the renewable emergy from nature and the emergy from economy. The result shows that MG avocado uses a higher proportion of renewable emergy from nature (0.15) when compared to SP system (0.01).

The figures 3 a, b and c show the comparison of the main emergy index among avocado systems with other oleaginous crops (Takahashi and Ortega, 2010). The comparison shows that avocado systems are not as efficient as the other oleaginous crops due to the high values of transformity (Figure 3a). Although, the renewability index is higher than the soybean crops, the main raw material used to produce biodiesel in Brazil, and the result of avocado SP system is better than canola crop (Figure 3b). The values of ELR are very similar to the other oleaginous crop showing the same environmental impact and the values of EER are also similar, showing the same trend, that is, the emergy spent to produce the product is not paid fairly (Figure 3c).

4. CONCLUSIONS

Avocado emergy indices are similar to the other oleaginous crops and avocado systems have high values of renewability index despite the low efficiency (high transformity). It is possible that the production of avocado biodiesel can have a better performance because ethanol can be produced from the avocado pit. Thus, it appears that the avocado is a promising source for the energy matrix, but further studies considering the full production chain should be held to obtain more accurate conclusion.



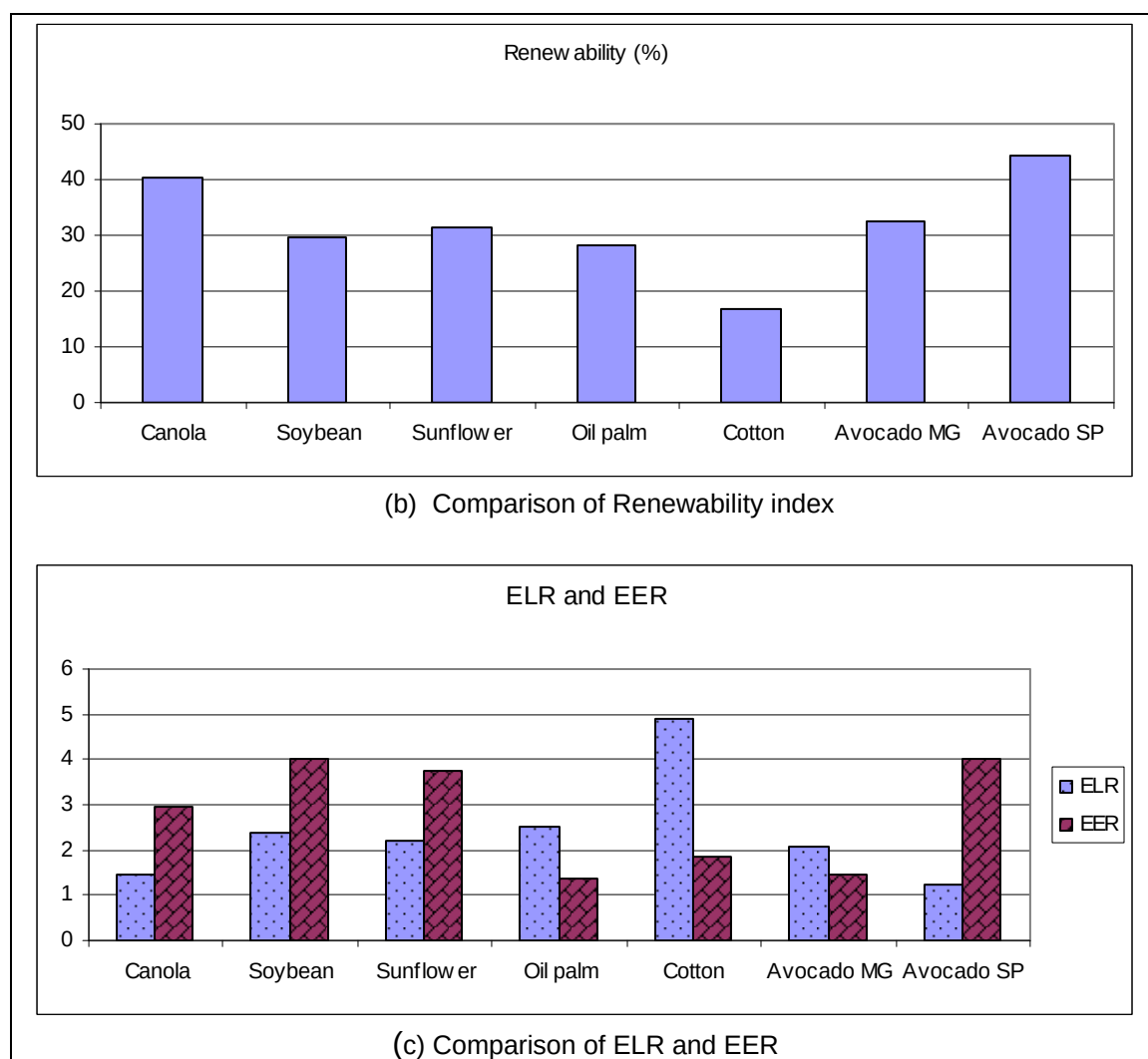


Figure 3. Comparison of energy indicators of oleaginous crop and avocado.

ACKNOWLEDGEMENTS

The authors are grateful to CNPq and Capes for the financial support.

REFERENCES

- Agostinho F., Diniz G., Siche R., Ortega E. 2008. "The use of emergy assessment and the Geographical Information System in the diagnosis of small family farms in Brazil". *Ecol. Model.* 210, 37-57.
- Agrianual. (2006). *Anuário da agricultura Brasileira*. Instituto FNP [Yearbook of Brazilian agriculture]. São Paulo, Brazil.
- ANP, 2010 National Petroleum Agency. Available at http://www.anp.gov.br/petro/dados_estatisticos.asp
- Brandt-Williams, S.L., 2002. *Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios. Folio No. 4—Emergy of Florida Agriculture*. Center for Environmental Policy, Environmental Engineering Sciences, Univ. of Florida, Gainesville, p. 40. Available at <http://www.emergysystems.org/downloads.php> (accessed 05.10.09).
- Brown, M.T., Ulgiati, S. *Emergy Analysis and Environmental Accounting. Encyclopedia of Energy*, 2: 329-354. 2004a.
- Brown M.T., Ulgiati S. 2004b. "Energy quality, emergy, and transformity: H.T. Odum's contributions to quantifying and understandings systems". *Ecological Modelling* 178, 201-213

- Coelho, O., Ortega, E., Comar, V. "Balanço de Energia do Brasil (Dados de 1996, 1989 e 1981)". In: *Engenharia Ecológica e Agricultura Sustentável*. 2003. Enrique Ortega Available at <http://www.fea.unicamp.br/docentes/ortega/livro/index.htm>.
- Cohen, M.J., Sweeney, S., Brown, M.T. "Computing the Unit Emergy Value of Crustal Elements." In: *Proceedings of 4th Biennial Emergy Conference, Emergy Synthesis 4, Theory and applications of the emergy methodology*. 2007. Center for Environmental Policy, Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL.
- Cresesp. 2010, *Centro de referência para energia solar e eólica Sérgio de Salvo Brito*. Available at www.cresesb.cepel.br
- Cuadra, M., Rydberg, T. "Emergy evaluation of the environment and economy of Nicaragua". In: *Proceedings of 1st Biennial Emergy Conference, Emergy Synthesis 1, Theory and applications of the emergy methodology*. 2000. Center for Environmental Policy, Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL.
- Demirbas M.F., Balat M., Balat H., 2009. "Potential contribution of biomass to the sustainable energy development". *Energy Conversion and Management* 50, 1746-1760
- Inmet. 2010. Instituto Nacional de Meteorologia. Available at www.inmet.gov.br
- La Rosa A.D., Siracusa G., Cavallaro L., 2008. "Emergy evaluation of Sicilian red orange production. A comparison between organic and conventional farming". *Journal of Cleaner Production* 16, 1907-1914.
- Martin, J.F., Diemont S.A.W., Powell E., Stanton M., Levy-Tacher S., 2006. "Emergy evaluation of the performance and sustainability of three agricultural systems with different scales and management". *Agriculture Ecosystems & Environment* 115, 128-140.
- Menezes, M.L., Lopes, L.F.S., Passaretti Filho, J. 2009. "Síntese de biodiesel empregando óleo de abacate". *Revista analytica* n44. 68-78.
- Odum, H.T., 1996 *Environmental Accounting, Emergy and Decision Making*. John Wiley, New York, pp. 370.
- Odum H.T. 1988. "Self organization, transformity, and information". *Science* 242, 1132-1139
- Ortega, E., Cavalett, O., Bonifacio, R., Watanabe, M., 2005. "Brazilian soybean production: emergy analysis with an expanded scope". *Bull. Sci. Technol. Soc.* 25 (4), 1–11.
- Ortega, E. 1998. *Tabela de transformidades*. Available at: <http://www.unicamp.br/fea/ortega/curso/transformid.htm>
- Pousa G.P.A.G., Santos A.L.F., Suarez P.A.Z., 2007. "History and policy of biodiesel in Brazil". *Energy Policy* 35, 5393-5398.
- Scienceman D.M. 1987. "Energy and emergy". In: Pillet G., Murota T, editors. *Environmental Economics: The Analysis of a Major Interface*. Geneva: Rolland Leimgruber, p.257-276
- Takahashi, F., Ortega, E. 2010. "Assessing the sustainability of Brazilian oleaginous crops – possible raw material to produce biodiesel". *Emergy Policy* 38
- Ulgiati, S., Brown, M.T., 1998. "Monitoring patterns of sustainability in natural and man-made ecosystems". *Ecol. Model.* 108, 23–36., 2446-2454.
- Ulgiati, S., Odum, H.T., Bastianoni, S., 1994. "Emergy use, environmental loading and sustainability. An emergy analysis of Italy". *Ecol. Model.* 73, 215–268.

APPENDIX 1

Minas Gerais system

R1 = 5.06 kWh/m²/day (Cresesb, 2010)

Energy = 5.06 kW/m²/day × 365 days/year × 10000m²/ha × 3.6 × 10⁶ J/kWh = 6.65E13 J/ha/year

Transformity = 1 seJ/J (Definition)

R3 = 1621 m³/ m²/year (Inmet, 2010)

Energy = 1621 m³/ m²/year × 5.0 E3 J/kg × 10000m²/ha × 1000kg/m³ = 8.11E10J/ha/year

Transformity = 31000 seJ/J (Odum, 1996)

N1 = 900 kg/ha/year (estimated)

Energy = 0.04 kg organic matter /kg soil × 5400 kcal/kg organic matter × 4186 J/kcal = 8.06E8 J/ha/year

M6 – Specific emergy = 1.68E12seJ/kg (Brown and Ulgiati, 2004)

M29 – Specific emergy = 8.03E12 seJ/kg (Ortega, 1998)

M36, M37, M38 – Specific emergy = 2.48E13 seJ/kg (Brown and Ulgiati, 2004)

M40 – Specific emergy = 7.2E13 seJ/kg (Cohen et al., 2007)

M41 – Specific emergy = 3.80E11 seJ/kg (Cuadra and Rydberg, 2000)

M50 – Specific emergy = 6.38E11 seJ/kg (Coelho et al., 2003)
M61 NPK 0-30-15 Ratio of molecular weight: $[P/P_2O_5]=0.437$ e $[K/K_2O]=0.83$
 Specific emergy = $0 \times 7.73E12 + 0.30 \times 0.437 \times 2.99E13 + 0.20 \times 0.83 \times 2.92E12 = 4.28E12$ seJ/kg
 Specific emergy N = 7.73E12 seJ/kg (Ortega, 1998)
 Specific emergy P = 2.99E13 seJ/kg (Ortega, 1998)
 Specific emergy K = 7.73E12 seJ/kg (Ortega, 1998)
M62 NPK 26-0-26 Ratio of molecular weight: $[P/P_2O_5]=0.437$ e $[K/K_2O]=0.83$
 Specific emergy = $0.26 \times 7.73E12 + 0 \times 0.437 \times 2.99E13 + 0.26 \times 0.83 \times 2.92E12 = 2.64E12$ seJ/kg
M3, S1-S8 Emergy per unit money = 5.02E12 (Coelho et al., 2003)

São Paulo system

R1 = 5.04 kWh/m²/day (Cresesb)
 Energy = 5.04 kWh/m²/day $\times$ 365 days/year $\times$ 10000m²/ha $\times$ 3.6 $\times$ 10⁶ J/kWh = 6.62E13 J/ha/year
 Transformity = 1 seJ/J (Definition)
R3 = 1508 m³/ m²/year (Inmet, 2010)
 Energy = 1508 m³/ m²/year $\times$ 5.0 E3 J/kg $\times$ 10000m²/ha $\times$ 1000kg/m³ = 7.54E10J/ha/year
 Transformity = 31000 seJ/J (Odum, 1996)
N1 = 900 kg/ha/year (estimated)
 Energy = 0.04 kg organic matter /kg soil $\times$ 5400 kcal/kg organic matter $\times$ 4186 J/kcal = 8.06E8 J/ha/year
M6 – Specific emergy = 1.68E12 seJ/kg (Brown and Ulgiati, 2004)
M29 – Specific emergy = 8.03E12 seJ/kg (Ortega, 1998)
M35, M36, M37, M38 – Specific emergy = 2.48E13 seJ/kg (Brown and Ulgiati, 2004)
M40 – Specific emergy = 7.2E13 seJ/kg (Cohen et al., 2007)
M41 – Specific emergy = 3.80E11 seJ/kg (Cuadra and Rydberg, 2000)
M50 – Specific emergy = 6.38E11 seJ/kg (Coelho et al., 2003)
M61 NPK 0-30-15 Ratio of molecular weight: $[P/P_2O_5]=0.437$ e $[K/K_2O]=0.83$
 Specific emergy = $0 \times 7.73E12 + 0.30 \times 0.437 \times 2.99E13 + 0.20 \times 0.83 \times 2.92E12 = 4.28E12$ seJ/kg
 Specific emergy N = 7.73E12 seJ/kg (Ortega, 1998)
 Specific emergy P = 2.99E13 seJ/kg (Ortega, 1998)
 Specific emergy K = 7.73E12 seJ/kg (Ortega, 1998)
M3, S1-S6 Emergy per unit money = 5.02E12 (Coelho et al., 2003)

** Baseline after 2000 (unit emergy value $\times$ 1.68)

CAN WE BREAK THE ADDICTION TO FOSSIL ENERGY?

Barcelona, Spain 19-21 October 2010

PARTICIPANTS

Feni Agostinho

State University of Campinas,
Food Eng. School
BR, Brazil
feni@fea.unicamp.br

Lucian Liviu Albu

Institute of Economic Forecasting
Romania
albul@ipe.ro

Beniamino Altezza

SGST Pisa
IT, Italy
beniaminobis@yahoo.it

Arturo Alfred Andersen Chinbuah

Universitat Autònoma de Barcelona, ICTA
ES, Spain
arturouv@gmail.com

Sabrina Arcuri

Università di Pisa Corso di Laurea in
Sviluppo e Gestione Sostenibile
dell'Ambiente
IT, Italy
sabbrinella87@hotmail.com

Himanshu Ardawatia

University of Bergen
NO, Norway
ardhimanshu@gmail.com

Pere Ariza-Montobbio

ICTA-UAB, Ecological Economics and
Integrated Assessment
ES, Spain
pere.ariza@uab.cat

Nancy Arizpe

Universitat Autònoma de Barcelona, ICTA
ES, Spain
nancy.arizpe@gmail.com

Vittoria Bandini

University of Bologna, CIRSA
IT, Italy
vittoria.bandini@unibo.it

Gualter Barbas Baptista

Universidade Nova de Lisboa,
CENSE
PT, Portugal
gualter@fct.unl.pt

Ugo Bardi

Università di Firenze,
Department of Chemistry
IT, Italy
ugo.bardi@unifi.it

Ligia Barna

INSA Toulouse, LISBP
FR, France
ligia.barna@insa-toulouse.fr

Sudhakara Reddy Basireddy

Indira Gandhi Institute of Development
Research, Energy and Environment
IN, India
sreddy@igidr.ac.in

Riccardo Basosi

University of Siena,
Department of Chemistry
IT, Italy
basosi@unisi.it

Andreu Bastardas López
Universitat Autònoma de Barcelona
ES, Spain
andreu.bastardas@gmail.com

Angel Antonio Bayod-Rújula
University of Zaragoza,
Electrical Engineering
ES, Spain
aabayod@unizar.es

Ivan Benes
CITYPLAN
CZ, Czech Republic
ivan.benes@cityplan.cz

Enrico Benetto
CRP Henri Tudor, CRTE
LU, Luxembourg
lucinda.eccli@tudor.lu

Lorenzo Benini
University of Bologna
IT, Italy
lorenzo.benini@unibo.it

Gioacchino Berardelli
University of Pisa
IT, Italy
gioacchino.berardelli@gmail.com

Alex Bertrand
Public Research Center Henri Tudor,
Resource Center for Environmental
Technologies
LU, Luxembourg
alexandre.bertrand@tudor.lu

Seth Blumsack
The Pennsylvania State University,
Dept. of Energy and Mineral Engineering
US, United States of America
sethb@psu.edu

Ryan Matthew Bright
Norwegian University of Science and
Technology (NTNU),
Energy and Process Engineering
NO, Norway
ryan.m.bright@ntnu.no

Mark T. Brown
University of Florida,
Center for Environmental Policy
US, United States of America
mtb@ufl.edu

Marcin Bukowski
Warsaw University of Life Sciences,
Chair of Agricultural Economics and
International Economic Relations
PL, Poland
marcin_bukowski@sggw.pl

Elvira Buonocore
Parthenope University of Naples, Italy,
Department of Environmental Sciences
IT, Italy
elvira.buonocore@uniparthenope.it

Ann Christin Bøeng
Statistics Norway,
Unit for Economic Growth and the
Environment
NO, Norway
abg@ssb.no

Laura Capra
Università di Pisa
IT, Italy
lauri410@gmail.com

Beatriz Carrasquer Álvarez
CIRCE, Natural Resources
ES, Spain
becarras@unizar.es

Engin Cetin
Pamukkale University,
Electrical & Electronics Engineering
TR, Turkey
ecetin@yahoo.com

Francesco Cherubini
Norwegian University of Science and
Technology (NTNU),
Energy and Process Engineering
NO, Norway
francesco.cherubini@ntnu.no

Fernando Círez Oto
University of Zaragoza,
Electrical Engineering Department
ES, Spain
pcirez@unizar.es

Marcel Coderch Collell
Comisión del Mercado de las
Telecomunicaciones
ES, Spain
mcoderch@cmt.es

Francois Diaz Maurin
Unaffiliated
US, United States of America
francois.diazmaurin@gmail.com

Jampel Dell Angelo
Universita Autònoma de Barcelona, ICTA
ES, Spain
jampeldellangelo@yahoo.it

Michael Dittmar
ETH Zurich, (Particle) Physics
CH, Switzerland
michael.dittmar@cern.ch

Vasile Dogaru
West University of Timisoara,
Nicholas Georgescu-Roegen
Interdisciplinary Formation and Research
Platform
RO, Romania
vdogaru@feaa.uvt.ro

Pinar Ertor Akyazi
Bogazici University,
Department of Economics
TR, Turkey
pinarertor@yahoo.com

Sandra Fahd
Parthenope University of Naples,
Sciences for the Environment
IT, Italy
sandra.fahd@uniparthenope.it

Kate Farrell
Universitat Autònoma de Barcelona, ICTA
ES, Spain
katharine.farrell@uab.cat

Laura Fastelli
University of Pisa,
Sviluppo e gestione sostenibile del territorio
IT, Italy
laura.fastelli@gmail.com

Brian Fath
Towson University,
Department of Biology
US, United States of America
bfath@towson.edu

Aldo Maria Femia
Istat, National Accounting,
Environmental Accounts
IT, Italy
femia@istat.it

Giacomo Fiaschi
Università di Pisa, corso di laurea in Sviluppo
e Gestione Sostenibile del Territorio
IT, Italy
giacofiaschi@yahoo.it

Valeria Fichi
University of Pisa,
Sviluppo e gestione sostenibile del territorio
IT, Italy
valeriafichi@gmail.com

Barney Foran
Charles Sturt University,
Institute of Land Water and Society
AU, Australia
Barney.Foran@gmail.com

Pier Paolo Franzese
Parthenope University of Naples,
Department of Environmental Sciences
IT, Italy
pierpaolo.franzese@uniparthenope.it

Jaume Freire González
ENT Environment and Management
ES, Spain
jfreire@ent.cat

Xavier Gabarrell Durany
Universitat Autònoma de Barcelona, ICTA
ES, Spain
xavier.gabarrell@uab.cat

Antonella Gagliardi

University of Bologna, Ravenna campus,
Environmental Management Research Group
IT, Italy

antonella.gagliardi@unibo.it

Kyrke Gaudreau

University of Waterloo,
Environment and Resource Studies
CA, Canada

kyrke.gaudreau@gmail.com

Tobias Gerstmaier

Concentrix Solar GmbH,
Department of Engineering
DE, Germany

tobias.gerstmaier@concentrix-solar.de

Patrizia Ghisellini

Alma Mater Studiorum,
University of Bologna,
Department of Protection and Valorization of
Agriculture and Food
IT, Italy

patrizia.ghisellini@unibo.it

Mario Giampietro

Universitat Autònoma de Barcelona,
Institut de Ciència i Tecnologia Ambientals
(ICTA)
ES, Spain

mario.giampietro@uab.cat

Charles A.S. Hall

State University of New York,
College of Environmental Science & Forestry
US, United States of America

chall@esf.edu

Myrna H.P. Hall

State University of New York,
Department of Environmental Studies
US, United States of America

mhhall@esf.edu

Tiina Johanna Häyhä

University of Jyväskylä,
School of Business and Economics
FI, Finland

tiina.hayha@uniparthenope.it

Nina Heidenstrøm

National Institute for Consumer Research,
Technology and Environment
NO, Norway

nina.heidenstrom@sifo.no

Raluca Ioana Iorgulescu

Siena College, USA,
Department of Economics
US, United States of America

riorgulescu@siena.edu

Kazuhito Ishimatsu

University of Surrey,
Centre for Environmental Strategy
UK, United Kingdom

k.ishimatsu@surrey.ac.uk

Bronia Jablonska

Energy research Centre of the Netherlands
(ECN),
Energy Technology in the Built Environment
NL, Netherlands

jablonska@ecn.nl

Maya Jobava

Durmishidze Institute of Biochemistry and
Biotechnology,
GE, Georgia

jobavam@mail.ru

Sheshti (Kersti) Lovisa Pravati Johansson

Uppsala University
SE, Sweden

johansson@sheshti.se

William Johnson

University of Georgia,
Faculty of Engineering
US, United States of America

williamj@uga.edu

Georgios Karakatsanis

National Technical University of Athens,
Rural & Surveying Engineering
GR, Greece

karakas11361@gmail.com

Mitsuyuki Kawakami
Tokyo Metropolitan University,
Graduate School of System Design
JP, Japan
kawakami@tmit.ac.jp

Christian Kerschner
UAB, ICTA
ES, Spain
christian.kerschner@gmail.com

Kevin John Krizek
Univeristy of Colorado,
Design and Planning
US, United States of America
krizek@colorado.edu

István Krómer
VEIKI Institute for Electric Power Research,
N.A.
HU, Hungary
i.kromer@veiki.hu

Pasqua L'Abbate
Politecnico di Bari, DICA
IT, Italy
p.labbate@poliba.it

Caterina La Grotteria
University of Pisa
IT, Italy
casagila@hotmail.it

Giacomo Lanza
NEST-IIT and Scuola Normale Superiore
IT, Italy
giacomo.lanza@sns.it

Anna Levin
Uppsala University,
Department of Social and Economic
Geography
SE, Sweden
anna.levin@kultgeog.uu.se

Xin Li
Sustainability Research Institute,
School of Earth and Environment
UK, United Kingdom
lec3xl@leeds.ac.uk

Roberto Lucini
Universitat Autònoma de Barcelona, ICTA
ES, Spain
robertolucini@alice.it

Tommaso Luzzati
Università di Pisa,
Dipartimento di Scienze Economiche
IT, Italy
tluzzati@ec.unipi.it

Henryk Michał Manteuffel
Warsaw University of Life Sciences,
Chair of Agricultural Economics and
International Economic Relations
PL, Poland
henryk_manteuffel@sggw.pl

Mads Ville Markussen
Risø National Laboratory for Sustainable
Energy, Technological University of
Denmark, Biosystems
DK, Denmark
mvil@risoe.dtu.dk

Leonardo Marotta
Entropia Snc, R&D
IT, Italy
leonardo.marotta@entropia-env.it

Alexandra Penedo de Sousa Marques
Instituto Superior Técnico,
Engenharia Mecânica
PT, Portugal
alexandra.marques@ist.utl.pt

Lorenzo Martellotta
Università di Pisa corso in Marketing e
ricerche di mercato
IT, Italy
loemarte85@gmail.com

Amaya Martínez
Universidad de Zaragoza - CIRCE
ES, Spain
amayamg@unizar.es

Igor Matutinović
GfK Center for Market Research
HR, Croatia, Republic of
igor.matutinovic@gfk.com

Kozo Mayumi

The University of Tokushima,
Faculty of Integrated Arts and Sciences
JP, Japan
mayumi@ias.tokushima-u.ac.jp

Stefano Meini

University of Pisa,
Department of Economy
IT, Italy
meo.ste83@hotmail.it

Salvatore Mellino

Parthenope - University of Naples,
Department of Sciences for the Environment
IT, Italy
salvatore.mellino@gmail.com

Robin E Moore

University of Georgia
US, United States of America
rem0913@uga.edu

Jakob Robert Müller

University Witten/Herdecke,
Economics & Management
DE, Germany
jakob.mueller@uni-wh.de

Giuseppe Munda

Universitat Autònoma de Barcelona, ICTA /
Dipt. d'Història Econòmica
ES, Spain
Giuseppe.Munda@uab.cat

David J. Murphy

SUNY-ESF / The Oil Drum,
Environmental Science
US, United States of America
djmurphy04@gmail.com

Elisa Sayoko Nakajima

State University of Campinas,
Food Engineering School
BR, Brazil
sayokonakajima@hotmail.com

Willem Petrus Nel

Sustainable Concepts
ZA, South Africa
willem@sustainableconcepts.co.za

Sophie Némóz

Université Libre de Bruxelles,
Centre for Studies on Sustainable
Development
BE, Belgium
sophie.nemoz@gmail.com

Sanderine, Nonhebel

University of Groningen,
Center for Energy and Environmental
Sciences
NL, Netherlands
S.Nonhebel@rug.nl

Ivo Johannes Opstelten

SEV
NL, Netherlands
opstelten@sev.nl

Enrique Ortega

State University of Campinas,
Food Engineering
BR, Brazil
ortega@fea.unicamp.br

Hanne Ostergård

Risø National Laboratory for Sustainable
Energy DTU, Technical University of
Denmark, Biosystems Division
DK, Denmark
hags@risoe.dtu.dk

Harun Kemal Ozturk

Pamukkale University
TR, Turkey
hkozturk@pau.edu.tr

David J. Packer

Springer
US, United States of America
David.Packer@springer.com

Rita Paleta
Instituto Superior Técnico
PT, Portugal
rita.paleta@ist.utl.pt

Alexandra Papathanasiou
Hellenic Ministry of Education,
University of Athens
GR, Greece
alexandra_papathanasiou@yahoo.gr

Maria Laura Parisi
University of Siena,
Department of Chemistry
IT, Italy
parisi11@unisi.it

Alberto Pasquini
Deep Blue
IT, Italy
alberto.pasquini@dbblue.it

Lucas Goncalves Pereira
State University of Campinas,
Food Engineering
BR, Brazil
lucasgp@fea.unicamp.br

Antônio Libório Philomena
Instituto Justiça Ambiental (IJA),
Conselho
BR, Brazil
alphilo@mikrus.com.br

John M. Polimeni
Albany College of Pharmacy and Health
Sciences
US, United States of America
jm.polimeni@verizon.net

Gaetano Protano
Parthenope University of Naples,
Sciences for the Environment
IT, Italy
protano.gaetano@libero.it

Jesús Ramos-Martín
Autonomous University of Barcelona, ICTA
ES, Spain
Jesus.Ramos@uab.es

Régis Rathmann
UFRJ, PPE/COPPE
BR, Brazil
rathmann@ppe.ufrj.br

Marco Raugéi
ESCI - Universitat Pompeu Fabra,
Environmental Management Research Group
(GiGa)
ES, Spain
marco.raugei@esci.es

Jens Rommel
Humboldt University Berlin,
Department of Agricultural Economics
DE, Germany
rommelje@hu-berlin.de

Franco Ruzzenenti
University of Siena,
Center for the Studies of Complex Systems
IT, Italy
ruzzenenti@unisi.it

Tinatin Sadunishvili
Durmishidze Institute of Biochemistry and
Biotechnology
GE, Georgia
sadunishvili_tinatin@yahoo.com

Julian Sagebiel
Humboldt University Berlin,
Department for Agricultural Economics
DE, Germany
julian.sagebiel@staff.hu-berlin.de

Ilaria Sbrana
Università di Pisa,
Facoltà di Economia
IT, Italy
isbrana@yahoo.com

Arnim Scheidel
Autonomous University of Barcelona, ICTA
ES, Spain
arnim.scheidel@uab.es

Hans Schnitzer

Graz University of Technology,
Institute for Process and Particle Engineering
AT, Austria
hans.schnitzer@tugraz.at

John R. Schramski

University of Georgia,
Biological & Agricultural Engineering
US, United States of America
jschrams@uga.edu

Tarik Serrano

ICTA - UAB
ES, Spain
tarik.serrano@uab.es

André Cabrera Serrenho

Instituto Superior Técnico - Technical
University of Lisbon, Environment and
Energy Scientific Area
PT, Portugal
andre.cabrera.serrenho@ist.utl.pt

Giuseppina Siciliano

University IUAV of Venice,
Department of "Territory. Economy.
Development and Sustainability"
IT, Italy
giuseppina.siciliano@gmail.com

Alevgul H. Sorman

Universitat Autònoma de Barcelona,
ICTA - Institute for Environmental Science
and Technology
ES, Spain
alevgul@gmail.com

Cátia Duarte Sousa

Applied Economics Research Center –
Lusófona University, Economics and
Management
PT, Portugal
catia.duarte.sousa@gmail.com

Nicolae Cristian Stanica

Institute of Economic Forecasting
Romania
stanica_cris@yahoo.com

Roger Strand

University of Bergen
NO, Norway
roger.strand@svt.uib.no

Eivind Stø

National Institute for Consumer Research
NO, Norway
eivind.sto@sifo.no

Kiti Suomalainen

IST, Technical University of Lisbon
PT, Portugal
kiti.suomalainen@dem.ist.utl.pt

Joseph Tainter

Utah State University,
Dept. of Environment & Society
US, United States of America
joseph.tainter@usu.edu

Fabio Takahashi

UNICAMP
BR, Brazil
fabiotak@gmail.com

Gail E. Tverberg

The Oil Drum
US, United States of America
info@tverbergactuarial.com

Gökhan Uçkan

University of Pamukkale,
Computer Engineering
TR, Turkey
guckan@pau.edu.tr

Sergio Ulgiati

Parthenope University of Napoli,
Department of Sciences for the Environment
IT, Italy
sergio.ulgiati@uniparthenope.it

Silvio Viglia

Parthenope University of Naples,
Sciences for the Environment
IT, Italy
silvio.viglia@uniparthenope.it

Luciano Vogli

University of Bologna, CIRSA
IT, Italy
luciano.vogli@gmail.com

Petra Wächter

Institute of Technology Assessment,
Austrian Academy of Sciences
AT, Austria
petra.waechter@oeaw.ac.at

Kimihiro Yamanaka

Tokyo Metropolitan University,
Graduate School of System Design
JP, Japan
kiyamana@cc.tmit.ac.jp

Amalia Zucaro

Parthenope University of Naples,
Department of Sciences for the Environment
IT, Italy
amalia.zucaro@uniparthenope.it

AUTHORS' INDEX

A

Agostinho F. 231
Albu L. L., 71
Alekklett K., 591
Amat E., 209
Andersen Chinbuah A., 529
Ariza-Montobbio P., 635

B

Bandini V., 463, 507
Bardi U., 111
Basireddy S. R., 39
Basosi R., 393, 655
Baudin I., 637
Bayod-Rújula A. A., 405, 517
Benes I., 577
Benesova Z., 577
Benetto E., 637
Benini L., 463, 507
Berntsen T., 119
Bertrand A., 433
Bøeng A. C., 351
Bravi M., 393
Bright R. M., 505
Brown M. T., 7, 703
Buchan K., 473
Bukowski M., 139
Buonocore E., 257

C

Cabrera Serrenho A., 597
Cabugueira M., 327
Carrasquer B., 129, 267, 395
Cavalett O., 497

Cetin E., 415
Cherubini F., 119
Círez F., 405
Colak M., 415
Comar, M. V., 611
Connors S., 385
Contin A., 463

D

D'Angelo S., 497
Deandrea G., 507
Diaz Maurin F., 579
Dittmar M., 149
Dogaru V., 99
Domingos T., 541, 597
Dudaui T., 457

E

Epema T., 565

F

Fahd S., 485
Fath B. D., 31
Femia A., 361
Ferrão P., 385
Ferraz, J. M. G., 611
Fiorentino G., 485
Foran B., 277
Franzese P. P., 257, 497, 553
Fraser R. A., 221
Freire González J., 667
Fthenakis V., 179
Fullana-i-Palmer P., 179

G

Gabarrell X., 209
Garlaschelli D., 655
Gasol C. M., 209
Gattie D. K., 51
Gaudreau K., 221
Ghisellini P., 197
Giampietro M., 17, 337
Gibson R. B., 221
Gonçalves Pereira L., 695
Gravitis J., 595

H

Hall C. A. S., 3
Hall M. H., 29
Häyhä T., 553
Hekim M., 415
Hertwich E., 119
Hubacek K., 169

I

Icli S., 415, 425
Iorgulescu R. I., 71
Ishimatsu K., 447
Ito K., 447

J

Jablonska B., 565
Jobava M., 457
Johansson S., 591
Juliano M., 385
Jury C., 637

K

Karakatsanis G., 81
Kasikci I., 415
Kawakami M., 441

Koster D., 433
Krizek K. J., 563
Krómer I., 319
Kvesitadze G., 457

L

Lavacchi A., 111
Leach M., 447
Levin A., 677
Li K., 51
Li S., 31
Li X., 169
Liljequist K., 591
Loubet P., 637
Luzzati T., 91

M

Manteuffel Szoegé H., 139
Marazza D., 463, 507
Markussen M. V., 495
Marotta L., 463, 507
Marques A., 541
Marshall J., 563
Martínez A., 129, 267, 395, 405, 517
Matutinović I., 309
Mellino S., 473, 485, 595
Metreveli B., 457
Mitani Y., 447
Monteiro Souza A., 595
Müller J., 185

N

Nakajima E. S., 695
Nathan, H. S. K., 39
Némoz S., 61
Nonhebel S., 159

O

Odum, E. C., 611
Ohlander L., 591
Oliver Solà J., 209
Opstelten I. J., 299, 565
Ornetzeder M., 647
Orsini M., 91,
Ortega E., 231, 595, 611, 685, 695, 715
Østergård H., 495
Ozturk H. K., 415, 425

P

Paleta R., 645
Parisi M. L., 393
Pasquini A., 543
Pereira L., 685
Peters G. P., 119, 505
Philomena A. L., 527
Polimeni J. M., 71
Protano G., 703

R

Ramos-Martín J., 625
Rathmann R., 599
Raugei M., 179
Recalde M., 625
Rieradevall J., 209
Rodrigues J., 541
Rommel J., 185, 575
Rommel K., 575
Rota C., 197
Rótolo G., 485
Rubio C., 129
Ruijg G. J., 565
Rutz Z. J., 51
Ruzzenenti F., 655

S

Sadunishvili T., 457
Sagebiel J., 575
Scacchi C., 637
Schaeffer R., 599
Schnitzer H., 289
Schramski J. R., 51
Schreuer A., 647
Siciliano G., 245
Silva C., 385
Siu Y. L., 169
Sorman A. H., 17, 337, 635
Sousa C., 327
Sousa T., 597
Stanica C., 71
Strømman A. H., 119, 505
Suomalainen K., 385
Szklo A., 599

T

Takahashi F. 715
Tedeschi A., 543
Tiezzi E., 393
Tiruta-Barna L., 637
Torri C., 463
Tverberg G. E., 371

U

Uche J., 129, 267, 395, 405
Uçkan G., 425
Ulgiati S., 7, 197, 257, 473, 485, 553, 595, 685, 703

V

Versteeg F. A., 299
Vetrella G., 361
Viglia S., 473, 595
Vogli L., 507

W

Wächter P., 647

Weterings R., 299

Willems E., 565

Y

Yamanaka K., 441

Yang Z., 31

Yaxley L., 111

Yilanci A., 415

Z

Zhang Y., 31

Zucaro A., 473, 685
