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The Problem of the Competitiveness of Nuclear Energy: A Biophysical Explanation

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ABSTRACT

In this study I try to explain the systemic problem of the low economic competitiveness of nuclear energy for the production of electricity by carrying out a biophysical analysis of its production process. Given the fact that neither econometric approaches nor one-dimensional methods of energy analyses are effective, I introduce the concept of *biophysical explanation* as a quantitative analysis capable of handling the inherent ambiguity associated with the concept of energy. In particular, the quantities of energy, considered as relevant for the assessment, can only be measured and aggregated after having agreed on a pre-analytical definition of a *grammar* characterizing a given set of finite transformations. Using this grammar it becomes possible to provide a biophysical explanation for the low economic competitiveness of nuclear energy in the production of electricity.

When comparing the various unit operations of the process of production of electricity with nuclear energy to the analogous unit operations of the process of production of fossil energy, we see that the various phases of the process are the same. The only difference is related to characteristics of the process associated with the generation of heat which are completely different in the two systems. Since the cost of production of fossil energy provides the base line of economic competitiveness of electricity, the (lack of) economic competitiveness of the production of electricity from nuclear energy can be studied, by comparing the biophysical costs associated with the different unit operations taking place in nuclear and fossil power plants when generating process heat or net electricity. In particular, the analysis focuses on fossil-fuel requirements and labor requirements for those phases that both nuclear plants and fossil energy plants have in common: (i) mining; (ii) refining/enriching; (iii) generating heat/electricity; (iv) handling the pollution/radioactive wastes.

By adopting this approach, it becomes possible to explain the systemic low economic competitiveness of nuclear energy in the production of electricity, because of: (i) its dependence on oil, limiting its possible role as a carbon-free alternative; (ii) the choices made in relation to its fuel cycle, especially whether it includes reprocessing operations or not; (iii) the unavoidable uncertainty in the definition of the characteristics of its process; (iv) its large inertia (lack of flexibility) due to issues of time scale; and (v) its low power level.

Keywords: Nuclear Energy, Nuclear Power , Nuclear Fuel Cycle, Fossil Energy, Electricity, Energy Accounting, Energy Analysis, Energy Return On Investment (EROI), Greenhouse Gas Emissions, Life-Cycle Assessment (LCA), Integrated Assessment, Energetics, Biophysical Economics, Bioeconomics, Energy Crisis

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EXECUTIVE SUMMARY

1. The aim of the study

The civil use of nuclear energy for the production of electricity has demonstrated a low economic competitiveness since the early stages of its development and it is very likely that the situation will remain the same in the future (Coderch Collell, 2009). As a matter of facts, the low economic competitiveness of nuclear energy appears to be a systemic problem. In this study I try to explain the roots of this systemic problem by carrying out an energetic analysis of the production of electricity through nuclear energy. In particular, I compare the various phases of this process of production to the analogous phases of the process of production of electricity with fossil energy.

2. The theoretical framework

Especially when dealing with energy, prices are not good variables to use in order to understand the characteristics of different primary energy sources. For instance, since the increase in the price of oil entails a depreciation of the US$ and other currencies used for its measurement, we are dealing with a clear case of impredicativity as the price affects the depreciation of the currency used to assess the price. In the same way, the adoption of national policies based on subsidies for the development and operation of primary energy sources entails that often the effects of market mechanism are obscured by political decisions. For these reasons econometric approaches are not useful to assess the quality of primary energy sources and it is important to look for a set of criteria capable of defining the quality of primary energy sources independently from prices.

Different types of methods based on biophysical variables have been proposed to provide a sound analysis of the relationship between energy quality and economic performance. However, the use of those methods of energy analysis poses several problems: (i) they do not address the unavoidable ambiguity of the definition of the label "energy"; and (ii) they remain one-dimensional, since they cannot handle the generation of quantitative assessments simultaneously across multiple scales, as it would be necessary (Giampietro et al., 2011a). Therefore, those conventional energy analyses are not effective at explaining the low economic competitiveness of nuclear energy in the production of electricity.

For this reason, a *biophysical explanation* of the difference in quality between different energy sources has to be based on a quantitative analysis capable of (1) handling the inherent ambiguity associated with the concept of energy; and (2) dealing simultaneously with multiple dimensions (multiple criteria of performance) *and* multiple scales. Although problems are also entailed when performing multi-dimensional energy analyses, they can be overcome by following some principles. In particular, the quantities of energy, considered as relevant for the assessment, can only be measured and aggregated after having agreed on a pre-analytical definition of a grammar characterizing a given set of finite transformations. A grammar consists in a set of expected relations linking semantic categories (the different energy forms used in the process) and formal categories (the relative quantification) according to a given set of production rules. Using this grammar it becomes possible to provide a *biophysical explanation* for the low economic competitiveness of nuclear energy in the production of electricity.

3. The grammar used for the comparison

The process of production of electricity (an energy carrier) starting from a given Primary Energy Source (e.g. nuclear, coal, hydro) requires a series of different processes. Therefore, in order to be able to compare different processes of electricity generation in relation to their performance and relative "costs" it is important to individuate and define the set of tasks and relative compartments to be used for the assessment. This translates into the pre-analytical choice of a grammar defining: (i) the semantic categories used in the representation of the process (primary energy sources, energy carriers, set of conversions, labor input, etc.); (ii) the formalization of these categories into quantitative assessments; and (iii) the production rules determining relevant quantitative results. For example, when dealing with the assessment of the quality of nuclear energy in the production of electricity, the grammar individuates the set of energy transformations across different energy forms that take place within the nuclear energy sector.

A few examples of grammar are provided in this report to contextualize the peculiarity of the production of electricity with nuclear energy in relation to other primary energy sources (PES). This comparison clearly indicates that nuclear energy and fossil energy present a striking similarity in the structure of their energy transformations. In fact, the various phases of the process of production of electricity are the same, with the only difference in the mechanism used to generate process heat.

This justifies the rationale of the study. Since the cost of production of fossil energy provides the base line of economic competitiveness of electricity, the (lack of) economic competitiveness of the production of electricity from nuclear energy can be studied, by comparing the biophysical costs associated with these two energy sources (nuclear and fossil) when generating process heat or net electricity when refining the analysis.

4. The results of the study

The major systemic problems of economic competitiveness with nuclear energy are found to be related to: (i) its dependence on oil, limiting its possible role as a carbon-free alternative; (ii) the choices made in relation to its fuel cycle, especially whether it includes reprocessing operations or not; (iii) the uncertainty in the definition of the characteristics of its process; (iv) its large inertia (lack of flexibility) due to issues of time scale; and (v) its low power level.

There are several factors making it difficult to define the characteristics of the process of generation of electricity with nuclear energy. First, there is a high variability of the uranium ore grades, and this fact determines large differences in the resulting assessment of the required inputs (costs) in the front-end phases of the process. Second, the time required to establish an operating process of electricity production with nuclear energy is much larger than the one typical of fossil energy powered plants: nuclear energy has a much longer time of immobilization of both the funds (the plant, the facilities for the handling of wastes) and flows (the nuclear fuel and nuclear waste), when compared with fossil energy. This uncertainty in the assessment of the biophysical characteristics of the process translates into a liability for the economic competitiveness of the civil use of nuclear energy for electricity production.

Now, leaving aside the issue of uncertainty, which is very relevant for private investors, the biophysical comparison between nuclear energy and fossil energy shows a systemic weakness of nuclear energy as an alternative energy source for the production of electricity. In fact, both indirect fossil-fuel (oil) and labor requirements are higher for nuclear energy than for fossil energy. Therefore, the fact that nuclear energy for the production of electricity remains dependent on the use of fossil-fuels (another energy carrier) and labor affects it economic competitiveness in comparison with fossil energy.

5. Conclusion

The biophysical explanation proposed here is based on the use of a grammar capable of analyzing the process of production of electricity in modular elements, defined using semantic and formal categories. In this way it becomes possible to individuate similarities and differences in the process of production of electricity, and then measure and compare "apples" with "apples" and "oranges" with "oranges". By adopting this approach, it becomes possible to explain the low economic competitiveness of nuclear energy in the production of electricity. More in general, the same approach can be used to assess the quality of other Primary Energy Sources in the production of electricity.

In more general terms, the problem of the low competitiveness of nuclear energy in comparison with fossil energy in making electricity can be seen first and foremost as a (systemic) problem of scale—both in space and time. By adopting this narrative the lack of competitiveness of nuclear energy can be explained looking at the very essence of this primary energy source, i.e. the scale of its *energy intensity*. The extreme density of nuclear energy requires a too large investment in the various steps of the process to dilute the energy flows to a level which can be handled by conventional technologies (the Rankine cycles used to transform thermal energy into mechanical energy). In a way we can see in the too high density of nuclear energy the opposite problem found with direct solar radiation, too diluted and requiring large investments to be concentrated into usable forms. The fundamental consequence of this energy intensity dilemma is that neither solar energy nor nuclear energy can maintain the current metabolic pattern of modern society based on the massive use of fossil fuels as primary energy sources.

LIST OF ABBREVIATIONS

ANDRA French Radioactive Waste Management Agency *(Agence Nationale pour la Gestion des Déchets Radioactifs)*
BWR boiling water reactor
CEA French Atomic Energy Commission *(Commissariat à l'Energie Atomique)*
CCS carbon capture and storage
CO2 carbon dioxide
EIA U.S. Energy Information Administration
EMR exosomatic metabolic rate
EPA U.S. Environmental Protection Agency
EPR Evolutionary Power Reactor (formerly European Pressurized Reactor)
EROI energy return on (energy) investment
GDP gross domestic product
HH household sector
HLW high level waste
IAEA International Atomic Energy Agency
IGCC integrated gasification combined cycle
ILW intermediate level waste
ITER International Thermonuclear (fusion) Experimental Reactor
LLW low level waste
LWR light water reactor
MIT Massachusetts Institute of Technology
MOX mixed oxide
NEI U.S. Nuclear Energy Institute
NRC U.S. Nuclear Regulatory Commission
OECD Organisation for Economic Co-operation and Development
PC pulverized coal
PES primary energy sources
Pu plutonium
PW paid work sector
PWR pressurized water reactor
SNF spent nuclear fuel
tce ton of coal equivalent
TET total exosomatic throughput
THA total human activity
toe ton of oil equivalent
U uranium
Udep depleted uranium
Urep reprocessed uranium
UO2rep reprocessed uranium fuel
VLLW very low level waste
WCI World Coal Institute

LIST OF UNITS

h	hour
J	joule
t	metric ton (10^3 kg)
W_{el} or We	watt electric
Wh_{el}	watt-hour electric
Wd_{th}	watt-day thermal
SWU	separative work unit

LIST OF SI UNIT PREFIXES

k	kilo (-10^3)
M	mega (-10^6)
G	giga (-10^9)
T	tera (-10^{12})
P	peta (-10^{15})

Make everything as simple as possible, but not simpler.
Albert Einstein

1. INTRODUCTION AND OBJECTIVES

1.1 Introduction

The civil use of nuclear energy for the production of electricity already went through difficult times from the mid-1970s to the 1990s, when the world turned its back to this industry, with some exceptions such as in France where the nuclear industry is ruled by the State. However, contrary to popular belief, the end of the first era of nuclear fission energy did not happen as a consequence of the accidents at nuclear power reactors of Three Mile Island (United States, 1979) and Chernobyl (Ukraine, 1986) but earlier and because of its low economic competitiveness. Indeed, a wave of cancellations of nuclear reactors started in 1974 in the U.S. immediately followed by a period of cessation of new orders until the early 2000s, so that almost all nuclear reactors that are now in operation in the U.S. were ordered in the period from 1965 through 1973 (Bodansky, 2004). During that period—called “great bandwagon market”—nuclear power was expected to soon become cheaper than coal-fired power, which *belief* turned out to be wrong (Yang, 2009). Although orders of nuclear reactors were sustained until a year after the oil embargo in 1973 with investors thinking that the economy would rely more on electricity after the oil crisis (Yang, 2009), the widely expected cost decline never happened (Bupp and Derian, 1978; Grubler, 2010) so that nuclear energy for the production of electricity was not competitive enough to gain interest from investors.

Today, despite a global economic crisis and urgent need for finding alternative energy sources in order to prepare the transition toward the post-oil era, nuclear energy still has trouble to convince investors of Western countries. For instance, in the U.S. the number of applications for new reactor licenses submitted to the Nuclear Regulatory Commission (NRC) has actually decreased over the last few years despite the federal 2005 Energy Policy Act (U.S. Congress, 2005) proposing tax incentives and loan guarantees for building new reactors (Bradford, 2010). Delays and over-costs encountered for the first reactors of third generation (French EPR) that are still under-construction in Finland (until 2013) and in France (until 2014) also undermine the chances of a second era of nuclear fission reactors in Europe (Bidwai, 2011). Worldwide, since the nuclear fission market is locked both in Europe and in the U.S.—where the design certification of the EPR is also being delayed by the NRC (Bidwai, 2011)—it seems very difficult that a “nuclear renaissance” could actually happen by relying only on growing economies of developing countries acquiring new nuclear reactors. Now, with the still unfolding Fukushima nuclear accidents in Japan—which started on March 11, 2011 after the Tohoku-Kanto earthquake and follow-up tsunami—that will continue until (at least) January 2012 (BBC, 2011), chances are that the worldwide nuclear slowdown will continue, as indicated by the German decision to phase out nuclear energy from its portfolio of Primary Energy Sources (Fairley, 2011).

In conclusion, nuclear energy for the production of electricity has demonstrated a low economic competitiveness since the early stages of its development and it is very likely that the situation will remain the same in the future (Coderch Collell, 2009)[1]. As

1 Especially if further safety measures in the licensing and design of reactors are to be added as a

a matter of facts, the low economic competitiveness that has been part of the past, present and (most probably) future of nuclear energy appears to be a *systemic* problem. The purpose of this article is trying to understand what are the reasons behind this systemic problem.

1.2 The context of the study

In this study I try to explain the systemic problem of the low economic competitiveness of nuclear energy by carrying out a biophysical analysis of the production of electricity through this energy source. I define here the intellectual and theoretical context in which the energy analysis is embedded.

First, this study embraces the *post-normal* science paradigm introduced by Funtowicz and Ravetz (1990) in contrast to *normal* science. Post-normal science acknowledges the unavoidable existence of non-equivalent perceptions and representations of the reality, legitimate but contrasting perspectives found among social actors, and heavy levels of uncertainty. In other words, the post-normal science paradigm aims at improving the *quality* of the discussion about sustainability issues rather than vainly looking for 'the best course of action' for society which is the objective of normal science (Giampietro et al., 2006). This implies changing the focus of discussion *from truth to quality* by enlarging the variety of methods, criteria and actors involved in the *assessment*[2] of the validity and relevance of the scientific output (for a more detailed description see Chapters 4 and 5 of Giampietro et al., 2011a). The present study fits into this post-normal science paradigm by (1) emphasizing in the need for handling of multi-dimensional analyses (multiple criteria) *and* multiple scales; and (2) acknowledging possible sources of uncertainty and ignorance.

Second, as shown by Giampietro and co-workers (2011a), the economic performance of modern societies can be explained using different biophysical indicators. This demonstrates the existence of a relationship between the performance of the economy and the energy sector and justifies the concept of *biophysical explanation* for the low economic competitiveness of nuclear energy for the production of electricity.

Third, this study adopts a biophysical representation of the metabolism of socioeconomic systems through the flow-fund theoretical model of Georgescu-Roegen (1971). In this model, *flows* (e.g. energy inputs, material flows) refer to elements disappearing and/or appearing over the duration of the representation (time horizon of the analysis which is discussed in Section 6.2), while *funds* (e.g. capital, people) refer to agents that are responsible for energy transformations and are able to preserve their identity over the duration of the representation (for a more detailed description see Chapter 7 of Giampietro et al., 2011a).

1.3 Objectives of the study

The general motive behind this study is to assess the *quality* of nuclear energy in the discussion about alternative energy sources. However, we must understand how the nuclear energy system behaves prior to perform such a quality assessment. As a matter

response to the Fukushima nuclear accidents.

2 Assessment: a critical evaluation and analysis of information relevant for decision making. (Giampietro et al., 2006)

of facts, the very first objective of this study is to better understand the functioning rules of the most complex energy system ever developed by humankind. From this understanding, it will then be possible to find the reasons for the low economic competitiveness of nuclear energy by using a *biophysical explanation* (introduced in Section 2.2).

This study will act as the preliminary step toward the general motive evoked above by providing the benchmarks necessary for assessing the quality of nuclear energy as an alternative energy source. This corresponds to the next research effort that will especially focus on handling multiple scales (in addition to the multiple criteria considered in this study) through an *integrated assessment*[3].

1.4 Boundaries of the study

1.4.1 Climate change and energy supply issues

In the general discussion about "energy and society", research for alternative energy sources is motivated by the two challenges of climate change *and* peak oil, both with different specific implications on society. As a matter of facts, even if climate change would not be an issue, energy supply issues alone would force society to engage into a transition of its energy sector towards the unavoidable post-oil era. Therefore, this challenge is (at least) as important as climate change since the current situation shows more and more evidences that implications of energy supply issues would soon become a priority. Indeed, as expected by peak-oil analysts (Hirsch et al., 2005; Bardi, 2009; Murphy and Hall, 2010), the production of some major oil supply companies stopped rising in the first decade of this new century (Kerr, 2011; Kopits, 2011). As a result, despite the fact that those *regional* peaks of oil production do not necessarily mean that the *global* peak oil is passed, the latter remains very likely to happen in the mid-term, so that the question of its exact date of occurrence is not relevant anymore. Given their upcoming prevalence, this study will focus on energy supply issues, especially the question of finding viable and desirable alternative energy sources.

1.4.2 Civil and military uses of nuclear technology

In this study, I investigate the civil use of thermonuclear technology so that implications of the military use of this technology—e.g. nuclear proliferation—are not discussed here. Nevertheless, the "source-sink" relationship between nuclear fuel supply and military use of nuclear energy is a well known attribute of this technology. Indeed, weapon-grade nuclear materials—uranium and plutonium—mainly come as by-products of the uranium fuel cycle which "produces" both depleted uranium (U-238) after the enrichment stage and plutonium (Pu-239) after the fission reactions in the thermal nuclear reactor. However, the new strategic arms reduction treaty (New START) signed in 2010 between the U.S. and Russia—whose objective is to reduce by 30% the number of nuclear warheads (U.S. Department of State, 2010)—could invert this relationship. Indeed, the weapon-grade uranium (>90% U-235) could become a significant source of fuel-grade uranium—by being burned in thermal fission reactors

3 Integrated Assessment: the simultaneous appraisal of attributes of performance referring either to different dimensions (criteria and/or scales). It requires the simultaneous use of indicators developed in different disciplinary fields. (Giampietro et al., 2006)

after dilution down to less than <5% U-235—which remains a marginal source today.

1.4.3 Fission and fusion nuclear energy

Only nuclear *fission* energy is considered in this study as it corresponds to the only application currently performed from thermonuclear physics for industrial purposes (excluding thus medical applications)—mainly in the production of electricity[4]. Research about potential commercial application from nuclear *fusion* energy is achieving some progress as the experimental stage is expected to start in the mid-term—through the ITER project announced to be in operation by 2019—followed by a demonstration stage—the future DEMO prototype power plant—announced to be operational by 2040 (ITER Organization, 2011). However, I argue that society cannot realistically expect nuclear fusion to become a significant (primary) energy source for supplying electricity (an energy carrier) over the 21st century. Indeed, even the commercial application of nuclear fusion energy before the end of this century can be questioned as (i) there are still fundamental research questions that have not been answered yet by the community of nuclear fusion scientists—such as the experimental impossibility to reach a self-sufficient tritium breeding process necessary for fusion power plant operation (Dittmar, 2011a); (ii) there is a systemic problem when scaling-up a new nuclear power program mainly due to the different degree of complexity between academic-reactor operations and an operational-reactor fleet—which has been the case during the first nuclear fission energy era (Bupp and Derian, 1978; Yang, 2009; Grubler, 2010); and (iii) the deployment of fusion nuclear power plants would imply a nuclear-fuel cycle transition which requires from 50 to 100 years to happen (Deutch et al., 2010) which would be further delayed if a new fleet of Generation IV reactors is to be deployed in the mean time, or simply because of the existing technological lock-in that affects nuclear technology (Arthur, 1989; Cowan, 1990). For those reasons, nuclear fission energy is very likely to remain the only nuclear energy source over the 21st century and maybe beyond into the future. On that respect, expectations about the use of nuclear fusion energy appears to be out of (time) scale since—as discussed earlier in this section—energy supply issues would have to be addressed before this potential primary energy source becomes available.

4 The use of nuclear fission energy for the production of industrial process heat is not within the scope of this study although it represents on possible application of the same nuclear technology.

2. THE THEORETICAL FRAMEWORK

2.1 Critical appraisal of the conventional tools assessing the quality of primary energy sources

In this section, I show (1) how *econometric* (i.e. price-based) approaches to energy quality are not useful; and (2) how one-dimensional methods of *energy* analyses are not effective at explaining the low economic competitiveness of nuclear energy in the production of electricity. Then, I present the problems entailed by *multi-dimensional* energy analyses, and how they can be overcome.

2.1.1 Econometric analyses are useless

Since the supply of energy carriers is crucial for the performance of the economy (Smil, 2008; Giampietro and Mayumi, 2009; Giampietro et al., 2011a), it is well known that helping as much as possible the consumption of energy carriers in the economy—giving subsidies in various forms and keeping the cost of energy low to boost the total throughput—is beneficial for keeping the economic momentum. Now, taxing energy in order to reduce carbon dioxide (CO2) emissions—for other purposes than macroeconomic ones—would have the same effect as a high price of energy, i.e. resulting in depressing the economy. The problem is that since the *direct* cost of energy has always been negligible (around 3% of GDP), governments of developed countries have always had an incredible degree of freedom on energy prices (through subsidies, tax discount, and a variety of other ways to help the energy industry) to the extend that they now can also implement differentiated taxation. This entails that prices are not good variables to use in order to understand the characteristics of different primary energy sources.

For instance, in the deregulated market of electricity, putting a price on CO2 emissions would artificially give advantage to nuclear energy against fossil energy assuming that the overall process of production of the former has lower total CO2 emissions than the latter (Deutch et al., 2003 and 2009). As a matter of facts, since the cost of production of fossil energy provides the base line of economic competitiveness of electricity, taxing CO2 emissions would increase the price of electricity. Then, in an attempt to avoid high taxes (due to a high flow of CO2 emissions), fossil energy would migrate to new technologies—such as advanced pulverized coal (PC) and integrated gasification combined cycle (IGCC) technologies—integrating carbon capture systems (CCS) as shown in Deutch and co-workers' study (2007). But, still, these new technologies would modify the cost of production of fossil energy and thus the cost of electricity.

From the example above, we see that an assessment of the quality of a primary energy source cannot be based on prices as they are subject to inequivalent factors of change. To make things more difficult, we cannot "make" energy so that the quality of primary energy sources depends on how much we have to invest in their exploitation and how much we get back from it (Hall et al., 1986; Giampietro and Mayumi, 2009). Then, since we need energy carriers to make energy carriers, there is a non-linear effect of direct and indirect costs associated with alternative energy sources when the output/input of energy carriers is low (for a more detailed discussion see Chap. 5 of Giampietro and Mayumi, 2009). This makes totally useless the econometric analyses in the discussion about energy issues as they attempt to extrapolate prices into the future. This is indeed the case for any energy analyses that—even indirectly—rely on econometric variables such as certain applications of the EROI or the average energy intensity methods to assess the energy embodiments, as shown in Section 2.1.2.

In conclusion, energy has never been a conventional commodity (in the past, when the price was getting too high the producers implemented policies to make it lower!) and its control depends more on military power and politics than on market prices. For instance, the adoption of national policies based on subsidies for the development and operation of primary energy sources entails that often the effects of market mechanism are obscured by political decisions. Moreover, since the increase in the price of oil entails a depreciation of the US$ and other currencies used for its measurement, we are dealing with a clear case of *impredicativity* as the price affects the depreciation of the currency used to assess the price (for a detailed description of the concept of impredicativity in energy analysis, see Chap. 6 of Giampietro et al., 2011a). For these reasons econometric approaches are not useful to assess the quality of primary energy sources and it is important to look for a set of criteria capable of defining the quality of primary energy sources independently from prices.

2.1.2 One-dimensional energy analyses are not effective

Conscious about the limits of using prices in the discussion about alternative energy sources, some analysts have been proposing different types of methods based on biophysical variables as an attempt to provide a sound analysis of the relationship between (their relative definition of) energy quality and economic performance. Early works about the analysis of economic performance based on the concept of energy date from the late 1970s and 1980s (Cleveland et al., 1984; 2000; Hall et al., 1986; Gever et al., 1991; Kaufmann, 1992; Hall, 2000; Ayres et al., 2003; and Ayres and Warr, 2005; in: Giampietro and Mayumi, 2009). Different methods were developed including methods based on the reading of thermodynamics. Here, I demonstrate that the use of those one-dimensional methods entail different types of problems when dealing with energy quality which makes them not an effective way to explain the low economic competitiveness of nuclear energy for the production of electricity—or any other primary energy source.

2.1.2.1 Emergy analyses

Beside his important contribution to the comprehension of energy and material flows within and between the environment and society (Odum, 1971), H.T. Odum also attempted to provide insight on the relation between energy inputs and economic performance through the use of the concept of *emergy* (Odum, 1996). Emergy analyses intend to measure quality differences between different energy forms by aggregating them into one single number corresponding to the quantity of embodied solar energy and crustal heat. This method has been largely criticized because of inherent theoretical and practical problems, such as its incongruence with the Second law of thermodynamics (Sciubba, 2010), or its dependence on the choices made for the boundaries of the study (Giampietro and Mayumi, 2009).

2.1.2.2 Net energy analyses

One of the most popular approaches is called the *net energy* analysis which compares the amount of energy delivered to society by a given technology to the total energy required in processing and delivering this energy in a useful form to the society. Net energy analyses imply the concept of *embodied* energy that corresponds to both direct and indirect energy costs for producing energy carriers. Early works about the analysis of economic performance based on the concept of embodied energy date from the late 1970s through 1980s (Herendeen and Bullard, 1976; Costanza, 1980; 1981; Hannon, 1981; 1982; Herendeen, 1981; 1998; and Slesser and King, 2003; in: Giampietro and Mayumi, 2009).

In net energy analyses, the evaluation of the *direct* costs is relatively easy as they correspond to the direct input of different energy carriers required to make another energy carrier (within the studied process of production). The problems rise when trying to quantitatively assess the *indirect* costs of production which correspond to all other energy carrier requirements both within the corresponding production sector and within the other sectors of the economy. Here, it is easy to understand the difficulty to define what the indirect costs are. For instance, the quantification of the energy inputs required for a given process (or an energy output) ultimately depends on the choice made when defining the boundaries of that process (for an analysis of the truncation problem in relation to the issue of multiple levels and scales see Giampietro and Mayumi, 2009). And to make things more complicated, the analyst has to deal with the complexity of modern society characterized by the interconnection (in terms of energy and material flows) of its various sectors.

Beside the problem of boundaries, net energy analyses face another issue of how to aggregate different forms of energy in order to get one number that make the analyst able to compare the performance of different energy sources. Net energy analyses offer different methods of energy aggregation which I discuss here.

- *Energy discounting*

The concept of energy discounting introduced by Hannon (1982) intends to take into account the changes over time of the “utility” of different energy forms to the society—just as it is commonly performed by economists with currency. However, the energy discounting method makes the same confusion as the Energy Return On Investment (EROI) analyses when accounting for energy inputs coming from different primary energy sources, as discussed below.

- *Energy Return On Investment (EROI)*

The Energy Return On Investment (EROI) is a method of assessment based on the First law of thermodynamics which has been in use since the 1980s (Cleveland et al., 1984; Hall et al., 1986). The EROI is a number that is the output/input ratio between the amount of energy we get from the energy system (output) and the amount of energy required to make this energy (input). However, this method is not satisfactory because of the unavoidable ambiguity of the definition of the label “energy” (Giampietro and Sorman, 2011). In the case of nuclear energy for instance, the “energy inputs” required in the various phases of the electricity production process correspond to different energy carriers (electricity and fuels), which, to make things more complicated, can be generated using different primary energy sources (PES). This is a systemic problem making impossible to generate a crisp output/input ratio in the case of the production of electricity, as shown below:

$$\text{EROI} = \frac{\text{Energy output}}{\text{Energy input}} = \frac{\text{Electricity}}{\text{Electricity} + \text{Fossil fuels} + \text{Coal} + \text{Gas} + ...} = \frac{\text{kWh}}{???}$$

The quantification of the semantic labels—energy input and energy output—is impossible in substantive terms (for a more detailed discussion see Chapter 9 of Giampietro et al., 2011a). This problem partly explains[5] why there have always been wide discrepancies of results between published EROI studies of nuclear energy in the production of electricity, as shown in Figure 2.1.

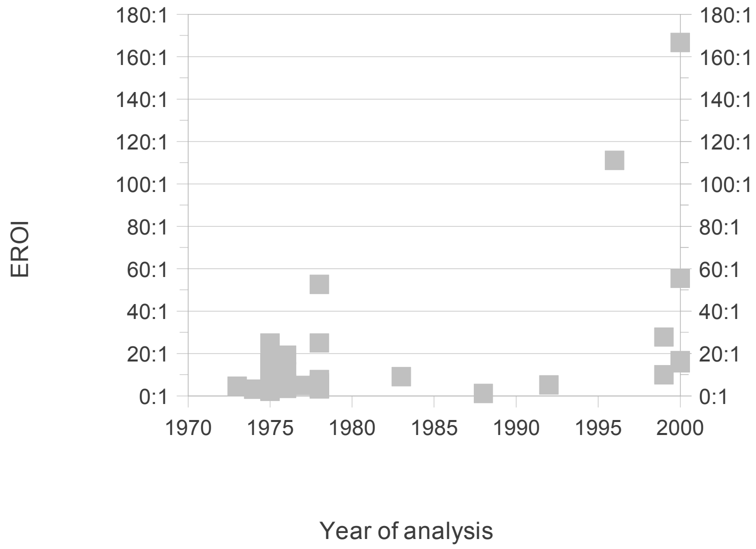

Figure 2.1: Summary of EROI results for nuclear energy plotted vs. year of analysis (Source: after Lenzen, 2008)

Figure 2.1 illustrates well the discrepancy on the EROI number of nuclear energy discussed before. This discrepancy has already been shown by Hall (2008a) using a smaller number of studies. In Figure 2.1, the discrepancy is even higher with an EROI varying from 0.6:1 to 166:1!

Changes in the technology of the nuclear energy process of production can partly explain having higher EROI numbers in recent studies against older ones[6]. However, the fact that the discrepancy on the EROI numbers remains between recent studies demonstrates the limits of using this one-dimensional method when assessing the quality of primary energy sources. Indeed, as explained by Giampietro and Mayumi (2009), "*the energy return on investment (EROI) is one of the most important concepts when studying the quality of alternative energy sources, but also one of the most*

5 The other reason for the observed discrepancy in the literature of EROI applied to nuclear energy is that EROI analyses are affected by the same problem of choices in the boundaries of the study as for exergy analyses.

6 Actually, as shown in Section 4.6, considering a better enrichment method—which is the most sensitive variable that have a "negative" (decreasing) effect—does not imply significant changes in the biophysical requirements of the whole nuclear energy system.

controversial. [...] (V)ery often, in many applications to energy analysis, the EROI is considered as merely an output/input ratio determining a net surplus of energy, without consideration being given to the time dimension, or the power level at which the flows are invested and supplied." This fact has now been acknowledged even by early proponents of EROI who would agree with saying that the concept of EROI in studying the quality of alternative energy sources is *necessary* but *not sufficient* (Hall, 2008a and 2008b; Murphy and Hall, 2010). For instance, it is now often coupled with the concept of energy payback period, which indicates the period after which the energy system starts producing a net surplus of energy. However, even with the use of those two concepts the systemic problem of EROI remains simply because, in that case, the energy payback period is derived from the EROI analysis.

As a matter of facts, in other to make it possible to calculate the overall EROI of an energy system—i.e. the energy cost of generating the required supplied of energy carriers in the other compartments—we need to provide 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 different categories of PES. As a result, the energy consumed by the energy sector, should not be considered as a "generic" loss to be summed to the others (Giampietro and Sorman, 2011).

One further problem found even in most advanced discussions about EROI (e.g. Murphy and Hall, 2010) is that in some cases EROI analyses are performed considering econometric-based methods of energy aggregation. Indeed, in their recent review of the existing literature about EROI, Murphy and Hall (2010) refer to such analyses—e.g. Cleveland (2005) for coal. However, as discussed earlier, the econometric approaches cannot be used in energy analysis. Indeed, in the case of an economic definition of EROI (i.e. GDP/energy consumed divided by the unit price of energy), taxes and subsidies can have a major effect in determining a distort picture of the role of price (Giampietro et al., 1993). Therefore, the degree of freedom of policy intervention is such that it is impossible to carry out any serious analysis using this specific definition of EROI. For the same reasons, multiplying the costs of nuclear energy processes with an economy wide average energy intensity is not an appropriate method to assess the energy embodiments of such processes neither (Lenzen, 2008).

As argued by Giampietro and co-workers (2011b), a proper use of EROI to assess the quality of primary energy sources must include the consideration of several relevant aspects: (i) the distinction between joules of primary energy source and joules of energy carrier; (ii) the key role of the output/input calculated over flows of energy carriers; (iii) the power level at which energy carriers have to be invested in the exploitation; (iv) the relative size of the required amount of PES and the net deliver of EC. In conclusion, the EROI (due to its derivation from financial analysis) should be about the speed of the return of investment and therefore cannot be handled in terms of a simple ratio over two numbers, which does not consider power levels nor the scale of the flows.

- *Exergy analyses*

Attempts to study quality of energy using *exergy* analyses—a sophisticated evaluation based on the Second law of thermodynamics—have been introduced by Robert Ayres and co-workers (2003). However, the definition of exergy depends on the reference environment considered in exergy analyses (Gaudreau et al., 2009). This entails a problem since, when dealing with large scale processes during several years and covering a large space domain, it is impossible to define a meaningful reference environment (Giampietro et al., 2011b). Since the optimization of the most irreversible process of a component based on an exergy analysis does not necessarily lead to the optimization of the system (Ahmadi et al., 2011), exergy analyses cannot be used to assess the quality of energy sources and, in any case, should not be used as a stand alone method in energy analysis. In conclusion, exergy is an extremely valuable tool for process-level analysis, but, although it shows good correlations with economic indicators, exergy shows shortcomings as a method to aggregate energy in an economic analysis because it is one-dimensional (Cleveland, 2005).

2.1.2.3 Conclusion

From this discussion about the problems related to the use of one-dimensional methods of energy analysis, we see that there is an epistemological challenge posed by the analysis of energy systems that demonstrates the need for handling simultaneously multiple dimensions in the integrated assessment of the quality of different energy sources.

2.1.3 Multi-dimensional energy analyses

When dealing with sustainability that is a multi-dimensional concept, there is no other choice than to perform a multi-criteria analysis. In energy analysis, for instance, it implies to characterize the performance of the energy sector considering a set of *relevant* and *non-reducible* criteria, which are related to non-equivalent objectives (Giampietro et al., 2006). On the other hand, the more dimensions (criteria and scales) are to be included in the characterization of the energy sector, the more difficult becomes the assessment, especially when requiring interdisciplinary cooperation between scientists. This leads to a first problem when dealing with multi-criteria energy analyses.

Now, let's assume that a team of interdisciplinary scientists successfully manages to build such a set of (relevant and non-reducible) criteria, and that they also manage to gather the data corresponding to each one of the criteria. Then, the problem is that *“no matter how good is the protocol specified for such an analysis, it is unavoidable that, according to the perspective, data and personal opinions of some other analyst, such a characterization could have been done in a better way.”* (Giampietro et al., 2006) Indeed, any multi-criteria energy analysis will always face some systemic problems such as (1) the unavoidable ‘openness’ of the information space; (2) incommensurability of trade-offs between criteria; (3) uncertainty (indeterminacy *and* genuine ignorance); (4) the quality of the problem structuring (on the normative side); (5) the quality of data (on the descriptive side); (6) the quality of the process of decision making (on the normative side); and (7) the quality of the handling of uncertainty throughout the whole process (Giampietro et al., 2006).

Nevertheless, when considered, those problems can be overcome by adopting some basic principles (Giampietro et al., 2006):

1. Keep separated the descriptive side (HOW/WHAT questions) from the normative side (WHY/WHAT questions);
2. Generate analyses that can learn in time;

3. Acknowledge the unavoidable presence of uncertainty in its broad sense (indeterminacy and ignorance);
4. Maintain the epistemological plurality between disciplines;
5. Avoid a dramatic hegemonization in the choice of relevant objectives and criteria (enlarging as much as possible to alternative perceptions);
6. Increase the transparency of the process of integrated assessment ("*making things as simple as possible, but not simpler*").

Now, after acknowledging the possibility of overcoming the systemic problems identified before, we are now left to find procedures that follow the above described principles. At that point, it shall be mentioned that performing an assessment only on the descriptive side (such as it is the objective behind the present study): (1) is only half-trip of the assessment process intending to provide a quality check of the energy sector (or for any other sustainability issue); and (2) doesn't not necessarily represent the starting point of the assessment process. Indeed, these two series of decisions that have to be taken on the descriptive and normative side depend on each other in a sort of chicken-egg relation. As a result, the assessment process should be performed iteratively using different analytical tools for performing a quality check both on the descriptive and the normative side.

Coming back to our general objective of assessing the quality of nuclear energy as an alternative energy source (discussed in Section 1.3), be aware that our study remains on the descriptive side by performing an assessment that intends to support the *discussion*—not the *decision* which belongs to the normative side. Nevertheless, as mentioned by Giampietro and co-workers (2006), even in such a *discussion*, social actors are necessary to provide EXTERNAL input (what is relevant in relation to the definition of good and bad) according to which the information space has to be constructed.

2.2 Introducing the concept of "biophysical explanation"

In order to overcome the problems discussed in Section 2.1.2, a *biophysical explanation* of the difference in quality between different energy sources has to be based on a quantitative analysis capable of handling *the inherent ambiguity associated with the concept of energy* (Giampietro and Sorman, 2011). Then, as a result of the discussion of Section 2.1.3, the quantities of energy considered as relevant for the assessment can only be measured and aggregated after having agreed on a pre-analytical definition of a *grammar* characterizing a given set of finite transformations. As already mentioned, a grammar consists in a set of expected relations linking semantic categories (the different energy forms used in the process) and formal categories (the relative quantification) according to a given set of production rules (for a more detailed description see Chapter 6 of Giampietro et al., 2011a). Because of its ability of establishing an agreed relation between the chosen semantic (perception of the issues) and the chosen formalization (representation of the issue) a grammar guarantees a shared meaning for the numbers developed within the grammar. That is, by using a grammar about which there is an agreement on its relevance, it becomes possible to provide a *biophysical explanation* based on quantitative assessment—considering different biophysical requirements in relation to the different energy forms involved in the process—for the low economic competitiveness of nuclear energy in the production of electricity.

3. THE GRAMMAR USED FOR THE COMPARISON

3.1 Defining a frame for analyzing the quality of nuclear energy

The process of production of electricity (an energy carrier) starting from a given Primary Energy Source (e.g. nuclear, coal, hydro) requires a series of different unit operations. Therefore, in order to be able to compare different processes of electricity generation in relation to their performance and relative "costs" it is important to individuate and define the set of tasks and relative compartments in charge for these unit operations to be used for the assessment. This translates into the pre-analytical choice of a grammar defining: (i) the semantic categories used in the representation of the process (primary energy sources, energy carriers, set of conversions, labor input, etc.); (ii) the formalization of these categories into quantitative assessments; and (iii) the production rules determining relevant quantitative results. For example, when dealing with the assessment of the quality of nuclear energy in the production of electricity, the grammar individuates the set of energy transformations across different energy forms that take place within the nuclear energy sector.

3.2 Schemes for nuclear energy in relation with other PES

In Figure 3.1, a few examples of grammar are provided to contextualize the peculiarity of the production of electricity with nuclear energy in relation to other primary energy sources (PES).

The following set of energy transformations (or conversions) is defined for the nuclear energy source:

- Conversion #1: PES to EC_{HEAT}
- Conversion #2a: EC_{HEAT} to EC_{MECA}
- Conversion #2b: EC_{MECA} to gross EC_{ELEC}
- Conversion #3: gross EC_{ELEC} to net EC_{ELEC} (End Uses)

In this grammar related to nuclear energy in the production of electricity, process heat and mechanical energy are introduced as energy carriers although they are not directly delivered to the society. The conversion #3 does not strictly correspond to an energy transformation but rather to a loss of EC due to the "energy for energy" dissipative part.

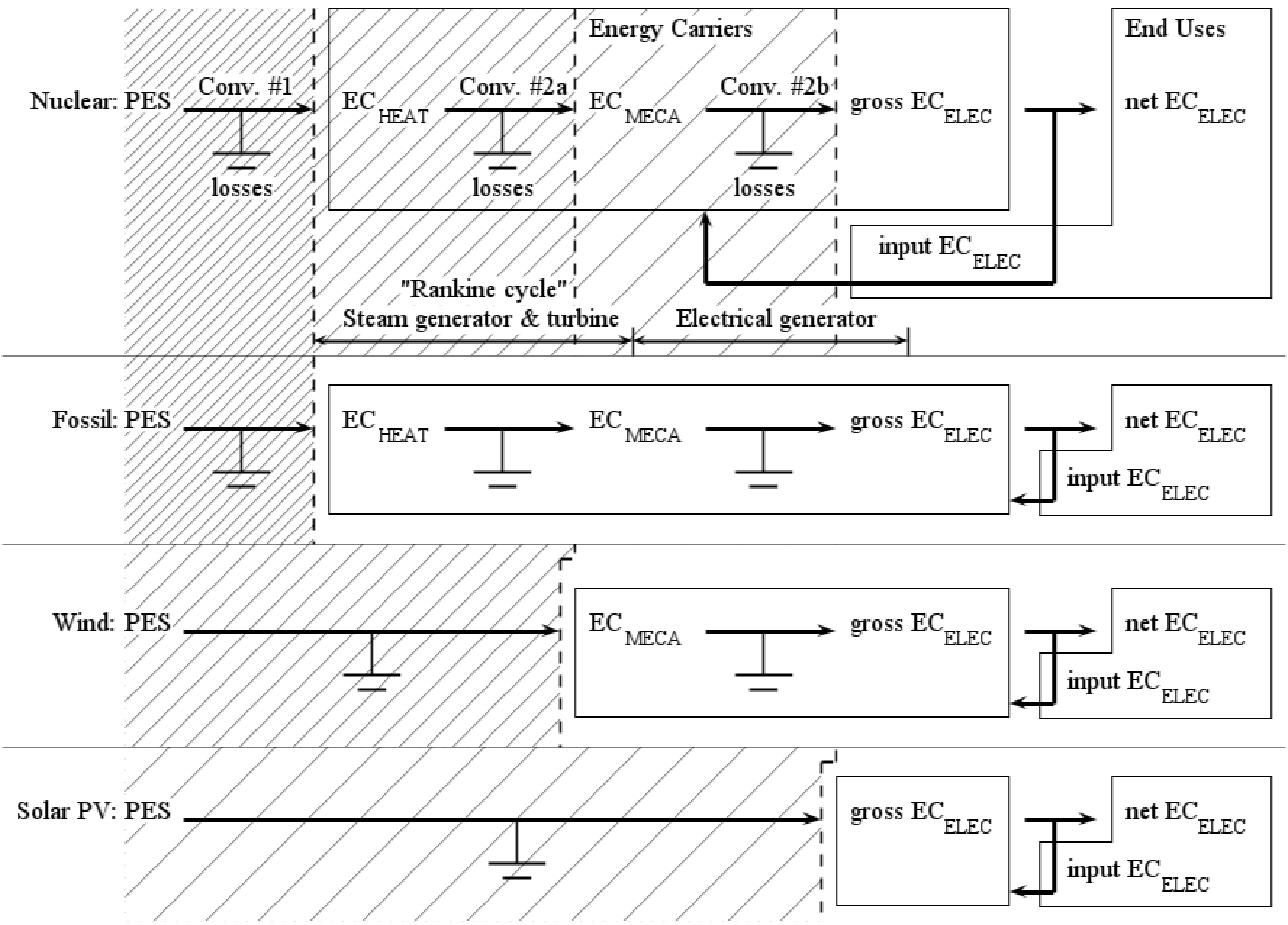

Figure 3.1: Examples of grammar of PES for the production of electricity

3.3 Implications of the schemes in assessing the quality of nuclear energy

This comparison clearly indicates that nuclear energy and fossil energy present a striking similarity in the structure of their energy transformations. In fact, the various phases of the process of production of electricity are the same, with the only difference in the mechanism used to generate process heat (conversion #1 in Figure 3.1). However, we will see in Section 4.3 that the two energy systems can present some qualitative and quantitative differences in the other energy conversions (mostly in conversions #2a and #3), so that they must be included in the study.

In Figure 3.2, I present a flow-fund scheme comparing the various phases of the nuclear energy process for the production of electricity to the analogous phases of the process with fossil energy. Those phases of the process of production represent the semantic categories used to carry out the quantitative assessment.

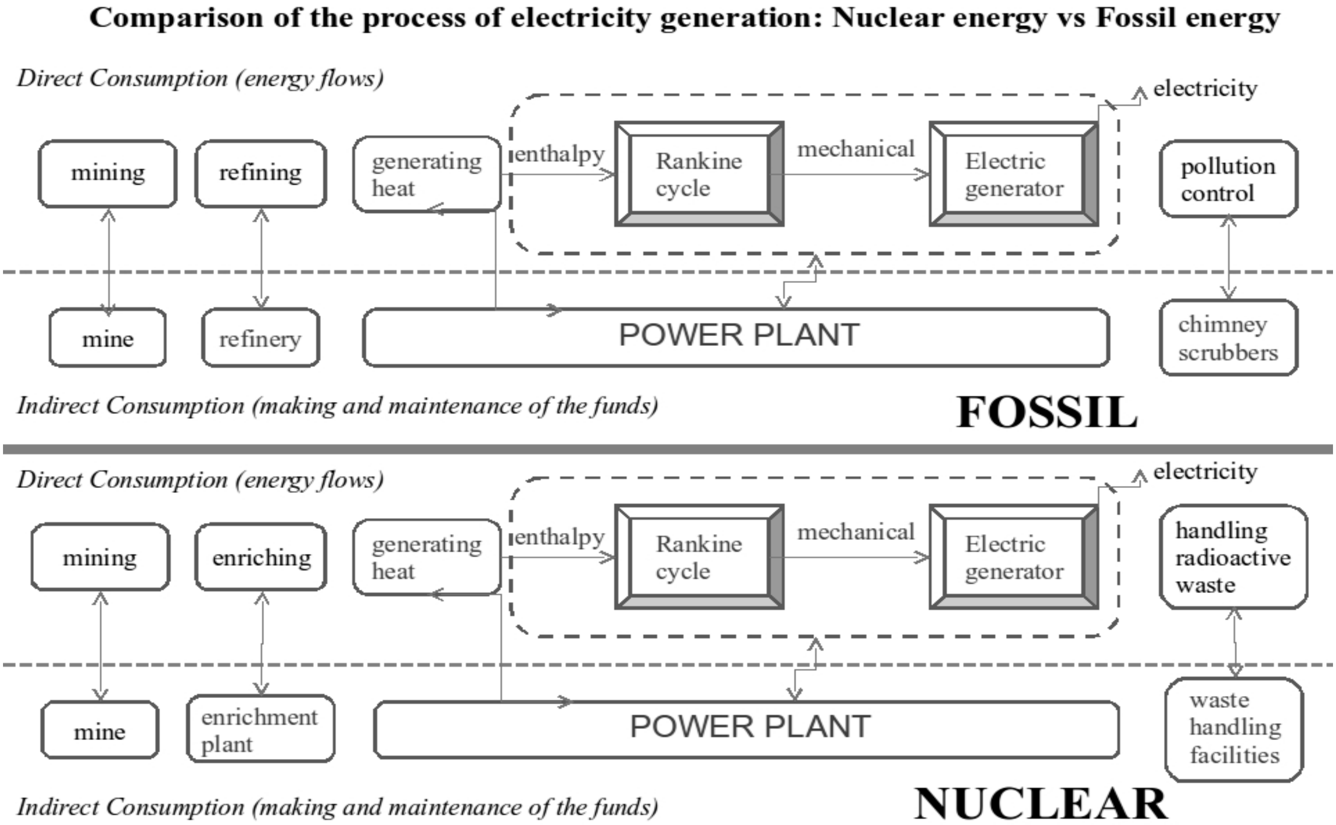

Figure 3.2: Comparison of the process of electricity generation: Nuclear energy vs. Fossil energy

This justifies the rationale of the study. Since the cost of production of fossil energy provides the base line of economic competitiveness of electricity, the (lack of) economic competitiveness of the production of electricity from nuclear energy can be studied, by comparing the biophysical costs associated with these two energy sources (nuclear and fossil) when generating process heat or net electricity (net EC_{ELEC}) when refining the analysis.

4. STUDY AND RESULTS

4.1 Comparison between nuclear energy and fossil energy

This section presents the comparison study between nuclear energy and fossil energy in making electricity. The study is a multi-criteria comparison considering several biophysical requirements. In order to compare the two energy systems, all biophysical requirements are expressed per unit of net electricity generated obtained after evaluation of the electricity requirements (input) and electricity generated (output) by the same system.

The main steps of the study performed for each system can be summarized as follows:
(a) Evaluation of the net electricity generated by the system (net GWh_{el}) to which different biophysical indicators can be compared;
(b) Evaluation of the specific biophysical requirements (unit per net GWh_{el});
(c) Sensitivity analysis on the results considering different variables for all four cases.

4.2 Description of the baseline cases used for the comparison

4.2.1 General discussion on the selection of the baseline cases

Two baseline cases are considered for each one of the two energy systems that are studied leading to a total of four cases identified throughout the study as follows:

- Case 1: Nuclear energy – Light Water Reactor (LWR) power plant;
- Case 2: Nuclear energy – LWR power plant with reprocessing;
- Case 3: Fossil energy – Integrated Gasification Combined Cycle (IGCC) power plant;
- Case 4: Fossil energy – IGCC power plant with Carbon Capture and Storage (CCS).

The selection of those two couples of baseline cases for the comparison between advanced technologies of fossil energy and nuclear energy systems for the production of electricity is mainly motivated by (1) the availability of the selected technology (Cases 1 and 3); and (2) the pace at which new designs can be deployed and become a representative technology in the worldwide electricity generation from either nuclear or fossil energy (Cases 2 and 4).

On that respect, advanced designs of fossil energy power plants including CO2 capture (Case 4) is considered as an available technology (or soon to be) whose deployment would be much faster than future generation of nuclear power plants (generation IV) for which technology is not yet available and whose deployment would require many decades (if they are to be deployed) before becoming a significant technology in the nuclear energy sector.

As far as the nuclear fuel cycle, according to an MIT study the LWR partly closed fuel cycle consisting in reprocessing the plutonium and uranium, implies a reduction of the enriched uranium fuel demand of about 15% and 10% respectively (Kazimi et al., 2011). According to the same study, the spent used nuclear fuel (SNF) can only be reprocessed one or two times (Kazimi et al., 2011). The partly closed fuel cycle is therefore currently used only as an experiment both in France and in the UK.

Its potential large scale deployment would require between 50 to 100 years (Kazimi et al., 2011) and since it also raises proliferation concerns it does not represent today a significant fuel cycle option. Nevertheless, it has been considered in this study (Case 2) in order to evaluate the effects of the reprocessing phase on the competitiveness of the overall nuclear energy process letting alone the problems raised above.

4.2.2 Case 1: Nuclear energy (LWR power plant)

For the nuclear energy production process, I consider the same baseline case of a typical 1300MWe light water reactor (LWR) power plant as used by Lenzen (2008) with a once-through nuclear fuel cycle meaning that no reprocessing is being considered during the whole process.

LWRs—including pressurized water reactors (PWR) and boiling water reactors (BWR)—represent about 90% of the worldwide installed capacity of nuclear power plants connected to the grid (CEA, 2010), while most new plants are on average 1300MWe—from 1000MWe to 1600MWe. The load factor of 79%—shown on Table 4.1—corresponds to the annual average load factor of all currently operating LWRs in the world (CEA, 2010). The burn-up value corresponds to the amount of thermal energy extracted from initial nuclear fuel in the reactor, expressed in gigawatt-days per metric ton of uranium (GWd_{th}/t_U). It depends on the nuclear fuel re-load of the reactor —$45GWd_{th}/t_U$ corresponding to the average value for LWRs (Lenzen, 2008). The uranium fuel consumption of $25t_U/y$ comes from the mass balance evaluation detailed in Section 4.4.1. This is consistent with the average values of $20t_U$/GWe per year (Kazimi et al., 2011) corresponding to about $26t_U/y$ for the selected baseline case. It shall be mentioned that the burn-up value depends only the nuclear reactor technology, not on the uranium ore quality. Indeed, as indicated before, the burn-up value is imposed by the frequency at which uranium fuel is re-loaded into the reactor while uranium fuel is adapted to the reactor type. The quality of uranium ore (grade or natural enrichment) then plays a role in the enrichment phase—the more the uranium grade, the more enrichment effort required as detailed in Section 4.5—and therefore ultimately influences the fuel consumption of the nuclear power plant.

Such a defined nuclear power plant generates about 100,000TJ of process heat (or enthalpy, in our case of an isobar process) and about $9,000GWh_{el}$ of (gross) electricity per year.

Parameter	Value	Unit	Source
Burn-up	45	GWd_{th}/t_U	Lenzen, 2008
Uranium fuel consum.	25	t_U/y	*see Table 4.5*
Process heat generated	97 600	TJ/y	
Plant capacity	1300	MW_{el}	Lenzen, 2008
Load factor	79%	(World av. for LWR)	after CEA, 2010
Electricity generated	9000	GWh_{el}/y (output)	
Rankine cycle efficiency (gross)	33%		

Table 4.1: Parameters of Case 1

4.2.3 Case 2: Nuclear energy (LWR power plant with reprocessing)

Case 2 differs from Case 1 by including a reprocessing phase into the nuclear energy production process. The reprocessing phase consists in recycling some of the used fuel (uranium and plutonium) as well as in reprocessing part of the depleted uranium leading to reducing the consumption of natural uranium. This phase is further detailed in Section 4.4.2. Table 4.2 presents the parameters of the baseline Case 2 which are essentially the same as Case 1 since the reactor technology itself remains the same. The only difference is that the nuclear energy production system is not only burning enriched natural uranium anymore but reprocessed fuel (mixed oxide fuel and reprocessed uranium) as well, so that the annual heated material consumption remains equal to $25t_{HM}/y$ as for Case 1.

Parameter	Value	Unit	Source
Burn-up	45	GWd_{th}/t_U	Lenzen, 2008
Heated material consum.	25	t_{HM}/y	*see Table 4.6*
Process heat generated	97 500	TJ/y	
Plant capacity	1300	MW_{el}	Lenzen, 2008
Load factor	79%	(World av. for LWR)	after CEA, 2010
Electricity generated	9000	GWh_{el}/y (output)	
Rankine cycle efficiency (gross)	33%		

Table 4.2: Parameters of Case 2

4.2.4 Case 3: Fossil energy (IGCC power plant)

For the fossil energy production process, a 380MWe Integrated Gasification Combined Cycle (IGCC) power plant using coal has been selected for the baseline case of this study. The coal-based IGCC technology, presented in Figure 4.5, corresponds to one of the new advanced designs of fossil-fueled power plants discussed in the 2007 MIT study (Katzer et al., 2007). The IGCC technology consists in turning the coal into gas in order to remove impurities before it is combusted, improving the overall efficiency of the power plant.

Contrary to nuclear energy, the burn-up (or heating value) of a fossil-fueled power plant does not depend on the selected technology but rather on the type of coal being mined the coal ore (e.g. bituminous, lignite, etc.). As a matter of facts, the heating value of 26GJ/t—shown in Table 4.3—has been calculated according to the proportion of each coal type being exploited in recoverable reserves (see Table 4.7). The coal consumption is equal to 1.2Mt/y (after Katzer et al., 2007) and the Rankine cycle efficiency is equal to 38% (Katzer et al., 2007).

Such a defined fossil-fueled energy power plant generates about 31,200TJ of process heat and about 3,300GWh_{el} of (gross) electricity per year.

Parameter	Value	Unit	Source
Heating value	26	GJ/t	*see Table 4.7*
Coal consum.	1.2	Mt/y	after Katzer et al., 2007
Process heat generated	31 200	TJ/y	
Rankine cycle efficiency	38%		Katzer et al., 2007
Electricity generated	3300	GWh_{el}/y (output)	
Load factor	75%		Rubin et al., 2007
Plant capacity	380	MW_{el}	

Table 4.3: Parameters of Case 3

4.2.5 Case 4: Fossil energy (IGCC power plant with CCS) – 90% of CO2 capturing

Case 4 differs from Case 3 by adding a carbon capture and storage (CCS) technology which reduces the CO2 emissions of the system by 90%. The IGCC technology is the leading candidate for electricity production with CO2 capture because it is estimated to have lower cost than pulverized coal with capture (Katzer et al., 2007; Rubin et al., 2007), which justifies our baseline case with IGCC and CCS technologies. Although those new designs are still under development—especially the CCS technology included in this Case 4—they represent the next generation of fossil-fueled power plants and are already being deployed in several places.

The CCS technology requires a certain amount of process heat (depending on the amount of CO2 being captured) mainly due to the gas-compression needed before injecting the carbon into the ground (see Figure 4.5) so that the Rankine cycle efficiency drops from 38% down to 31% (Katzer et al., 2007) as shown in Table 4.4. In order to maintain the same generation of about 3,300GWh_{el} of (gross) electricity per year, the coal consumption is therefore increased to 1.5Mt/y (after Katzer et al., 2007). The (gross) process heat of such a defined fossil-fueled power plant is equal to about 38,500TJ per year which difference with Case 3 is only due to the higher annual coal consumption. Then, the net process heat (35,700TJ/y) generated by the selected fossil-fueled energy power plant can directly be derived from the loss of Rankine cycle efficiency.

Parameter	Value	Unit	Source
Heating value	26	GJ/t	*see Table 4.8*
Coal consum.	1.5	Mt/y	after Katzer et al., 2007
Process heat generated	38 500	TJ/y (output)	
Rankine cycle efficiency	38%	(w/o CCS)	Katzer et al., 2007
	31%	(w/ CCS)	Katzer et al., 2007
Process heat generated	35 700	TJ/y (net)	
Electricity generated	3300	GWh_{el}/y (output)	
Load factor	75%		Rubin et al., 2007
Plant capacity	380	MW_{el}	

Table 4.4: Parameters of Case 4

4.3 Description of the general scheme of the study

As shown in Figure 4.1, a given succession of energy transformations (unit operations) is considered for this study. In that scheme, all biophysical requirements are expressed in their own units, even if they represent an energy form so that I do not perform any aggregation based on fixed conversions (the approach of reductionism) in terms of measurement units. The theoretical importance of such consideration is explained in Section 2. Note that in this study, I define the *energy system* as being the whole process (including all phases—the combination of all unit operations according to the specified grammar) of production of electricity, either using nuclear energy or fossil energy. As explained in Section 4.2, two different cases will be considered for each one of the nuclear and fossil technologies of electricity production leading to four distinct energy systems (or cases).

The different biophysical requirements entering into the whole process of each energy system are the following ones:

- Electricity input (kWh);
- Fossil fuels, including Oil (toe) and Coal (tce), from which the CO2 emissions (t_{CO2}) can be derived;
- Labor (h).

All those biophysical requirements are expressed per unit of (net) electricity generated (unit per kWh_{el}) so that the two energy systems (fossil and nuclear) can be compared. I will therefore speak of *specific* biophysical requirements when presenting the results.

In order to make possible the comparison, all cases must address the implications of the internal requirement of electricity of the system (see Figure 4.1) in order to evaluate the net electricity generated to which the biophysical requirements will be compared. This is of capital importance for the study because the whole process might differ in terms of net electricity generated, although the Rankine cycle efficiency of the power plants (producing the gross electricity) are of the same order of magnitude. Again, this study takes a systemic view and does not focus on one single part of the system (i.e. the power plant) but it analyses the competitiveness of the whole production process as explained in Section 3.

Figures 4.1 and 4.2 use the energy system language first proposed by H.T. Odum (1971) as a common denominator expressing all the flows and processes together in order to understand a whole system and the full interaction of the parts (Brown, 2004).

The elements in those figures have the following meanings:

- Rectangles with a semicircle on the right represent elements transforming low-quality energy flows under control interactions to high-quality flows (*producer*). Here, the Whole production process is generating the net supply of electricity from natural uranium. However, since this element is also consuming a part of the flow of the exosomatic energy carrier (electricity) it produces, the whole process is shown as containing all phases but the Rankine cycle (including the generator). Note that this symbol only corresponds to the producing function of the Whole process which includes internal consumption parts.
- Rectangles with an arrow on the sides represent interactive intersections (*interactions*) between two different flows (energy forms). Here, the Rankine cycle process is an interaction as it transforms the process heat into mechanical energy and then into electricity (considering the generator being part of the "Rankine cycle") consuming along the way part of the electricity (electricity input) that has been generated by the system. This is the reason why the Rankine cycle has been taken out of the whole process in Figure 4.1.
- Hexagon represent the consuming parts of the process (*consumer*). Here, the End-uses part is the consumer of the process.

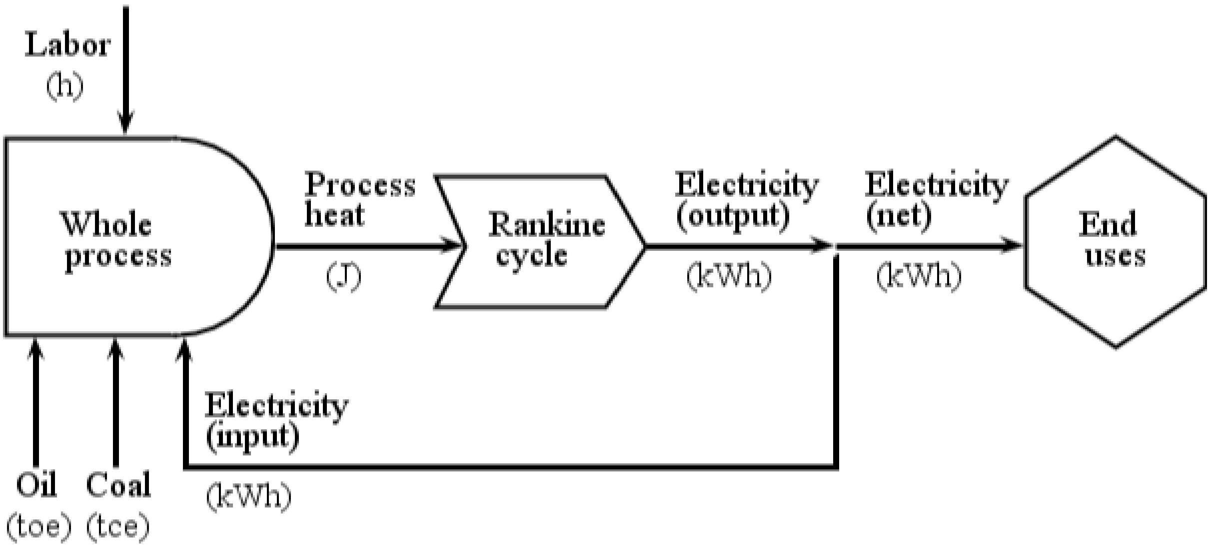

Figure 4.1: General scheme of the study (Cases 1 to 3)

As shown in Figure 4.2, the general scheme of Case 4 differs form the other cases by considering an additional internal requirement of process heat (J) due to the CCS technology as explained in Section 4.2.5.

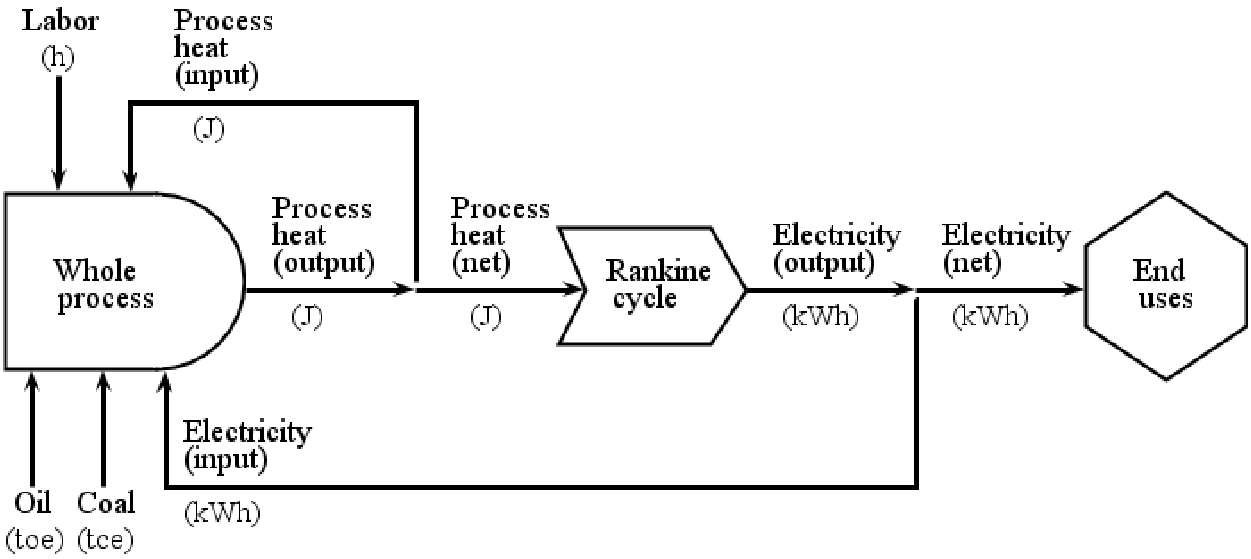

Figure 4.2: General scheme of the study (Case 4)

4.4 Evaluation of the material balances

In order to evaluate the different biophysical requirements for the four cases of the study, the annual material balance of each production process has been performed. Each material balance includes the different phases related to the fuel in all its successive forms—from the mining of ore to the handling of waste.

The mass balance evaluation is the most delicate step when studying nuclear energy (Cases 1 and 2) because (1) it requires making assumptions for several variables during each one of the different phases; and (2) there are non-linear relationships between the values taken by certain variables. In addition, the mass balance for those cases—and so does the results of the study—can be very sensible to the variables as discussed in Section 4.5.

For each case, a figure presents the material balance of the baseline case considered showing the different phases using the grammar presented in Section 3. Values shown in the figures are detailed in the corresponding tables.

4.4.1 Case 1: Nuclear energy (LWR power plant)

Figure 4.3 presents more in details what are the parts inside the whole process presented in Figure 4.1. In particular, the figure shows the three main phases of the process (1) Mining, (2) Enriching, and (3) Handling waste according to the grammar detailed in Section 3. For each one of those phases, some sub-phases are presented in hexagons allowing to reach the level of details necessary to perform the study.

As in Figure 4.1, Figure 4.3 uses Odum's energy system language including three additional symbols:

- Circles represent the low-quality energy in its natural environment (*source*). This source corresponds to the primary energy source (PES) directly used by the energy system, meaning that it does not include other PES indirectly used through the consumption of other energy carriers (EC) such as oil and coal. PES is not produced by the energy system. It is therefore important to track its consumption, since it maps onto emissions and rate of stock depletion. Since this problem affects all non-renewable resources[7]—not only fossil energy sources (oil, coal and gas) but also mineral energy sources such as natural uranium as shown in the figure—it represents one of the motives behind the study although stock depletion is not directly discussed in this study.
- Triangles with a semicircle on the bottom represent the energy storage compartments of the system (*tanks*). Although those storage compartments do not perform any energy transformation, they do consume different EC for the maintenance of the flows and funds. In the case of the nuclear energy system, those compartments correspond to the handling of waste (storage and disposal).
- Earth symbols represent energy losses (*sinks*) corresponding here to the material flows that go out of the system considered in the study because they do not fall under any phase anymore. In the case of nuclear energy, waste with low levels of radioactivity (LLW after storage and VLLW) go into the environment and do not require any further management efforts. Nevertheless, the sinks are important to be identified in order to maintain the mass balance of the whole process in equilibrium. On that respect it shall be noted that the mass balance equilibrium is only ensured for uranium material flows (t_U). Indeed, secondary products that go in and out the process during the various front end phases (Mining and Enriching) are not considered in the material flows so that the making and maintenance efforts of those flows are not included in the study.
  Note: Although Figure 4.3 shows that part of the LLW/VLLW are considered as

7 In reality, all resources *are* renewable. The non-renewable essence of resources is only due to a problem of scale related to humankind. In certain situations, the use of resources by humankind is performed at a much higher rate than the minimum rate at which it can be geophysically renewed. This is the rational behind the differentiation between *non-renewable* (primary) energy sources (oil, coal, gas, uranium) and *renewable* (primary) energy sources (wind, solar, hydro).

sinks, most of the radioactive waste coming from the different phases have to be handled (stored and/or disposed) which require additional biophysical requirements which explains why fossil energy as a major advantage as a primary energy sources compared to the nuclear energy since up to now emissions were going into the atmosphere without requiring a specific localization and corresponding biophysical requirements.

Internal interactions between the elements in Figure 4.3 are represented in the following ways:

- black lines are flows of PES in their various forms from the mining phase to the reactor;
- dotted lines are flows of waste (HLW, ILW and LLW) going to the last stage (handling of waste) and, thus, exiting the flow path going to the reactor. The flows of waste are important to be identified because they will imply significant biophysical requirements given their large values.

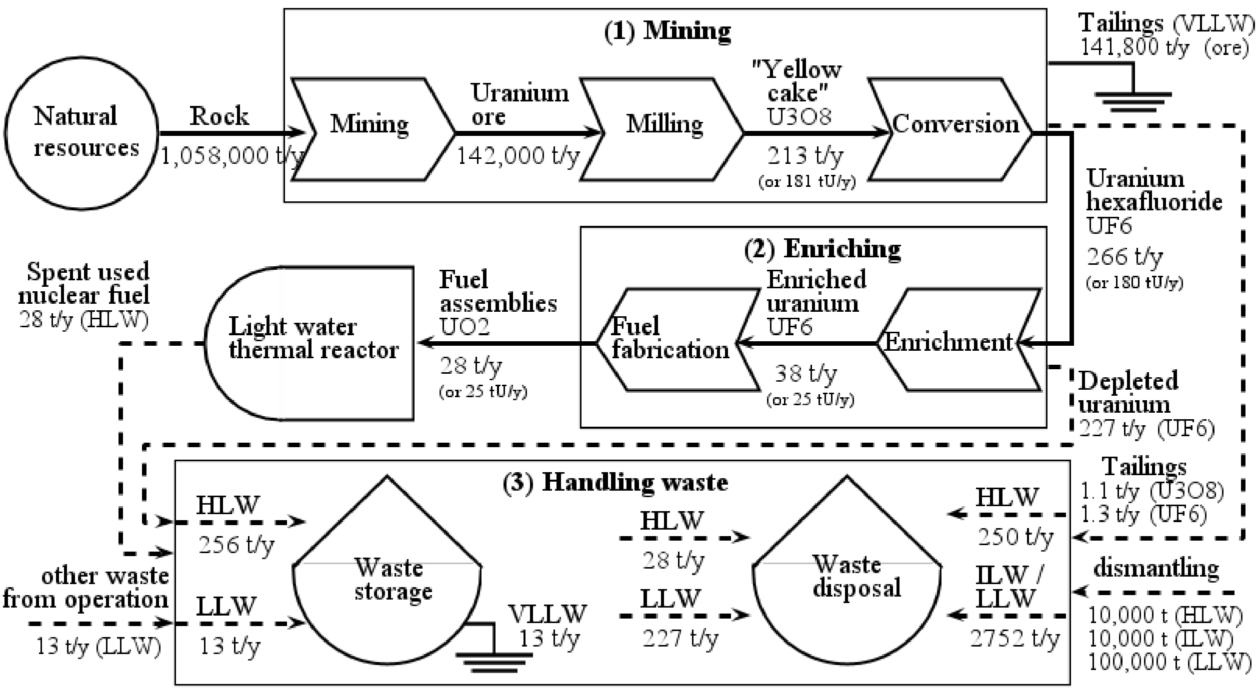

Figure 4.3: Mass balance of Case 1 (once-through nuclear fuel cycle)

Table 4.5 presents the calculations of the material balance of Case 1. In this table the following assumptions are considered:

- The overburden and waste rock which has to be removed to get access to the uranium ore in conventional uranium mines depends on the type of mines. Waste-to-ore ratio generally ranges from 20:1 to 1:1 for underground mines (with an average ratio of about 9:1) and from 5:1 to 1:1 for surface mining (US EPA, 2006). The average value of 7:1 has been evaluated based on the worldwide distribution of mining methods used to extract natural uranium (Lenzen, 2008). It shall be noted that since those waste are stored as waste piles generally close to the mining site, they do not enter into the material flows after the first front-end phase (mining).

- The ore grade—i.e. the content of natural uranium (U3O8 or "yellow cake" obtained after milling) in the ore extracted—varies significantly depending on the mines. The value of 0.15% U3O8 considered in the study corresponds to the baseline value of the study by Lenzen (2008).
- The recovery rate for uranium mining is expressed as a function of ore grade (% U3O8) as shown in Figure A.1 of the appendixes. The lower the ore grade, the less uranium is recoverable from the reserves. Storm van Leeuwen and Smith's regression (Ref. [30] in Lenzen, 2008) is shown in the figure with a trend line equation equal to:

$$f(x)=0.1241*\ln(x)+1.7465 \quad \text{with} \quad R^2=0.9617$$

  The trend line shows a better accuracy for lower values of ore grade (x < 0.1%-U3O8) with a slight divergence above this value which does not significantly affect the results since the ore grade value considered remains in the low range.
- The losses of materials during the milling, conversion and fuel fabrication processes are taken from Lenzen's study (2008).
- As explained in Section 4.2.2, I consider the same baseline case as used by Lenzen (2008). As a matter of facts, the assays (feed, tails and product) as well as the enrichment method distribution are taken from Lenzen's study.
- The mass balance of the uranium enrichment process has been evaluated adapting the calculator developed by the WISE Uranium Project (WISE, 2009a). This calculation can only be performed if one of the following four variables is known: enrichment effort, feed assay, tails assay or product enriched. When evaluating the mass balance, the last three last variables are not known. However, the characteristics of the reactor is known and so does its annual enrichment effort required. In the case of a LWR of 1GWe capacity, the annual enrichment effort—i.e. the separative work necessary in order to enrich the natural uranium up to the U-235 concentration required by the reactor—is about 120,000SWU (Hore-Lacy, 2004). Since, the enrichment effort is not a linear function of the reactor capacity, I stayed with this value for the study although the reactor capacity is 1.3GWe which is slightly conservative (lower enrichment effort than in reality) and represents the main assumption of the mass balance evaluation as all other variables indirectly depend on the value set for the enrichment effort. Results of the mass balance evaluation for the enrichment process are shown in Table A.1 of the appendixes.
- The amount of various operation and dismantling waste materials are taken from Lenzen's study (2008).
- The lifetime of the power plant is used to linearize the construction and dismantling capital costs that are spent before and after the life of the plant. In Lenzen (2008), the lifetime of the LWR baseline case is set to 35 years. However, lifetime of power plants can be longer than 35 years when extended beyond their initial design. In the study, the lifetime is set to 40 years corresponding to the high end for generation II reactors. This assumption is conservative as it leads to flatten the costs of the construction and dismantling processes.
- There are various types of materials that have to be handled by being stored and/or disposed depending on their respective levels of radioactivity which vary in time. The fact that radioactivity decays in time implies that some waste can

be temporarily stored without necessarily being disposed later. In the study, mining and milling tailings are directly disposed as LLW without storage (NRC, 2011a); spent *depleted* nuclear fuel[8] is stored as HLW and then disposed as LLW after deconversion (NRC, 2011b); and spent *used* nuclear fuel (SNF) is stored and then disposed as HLW. The other waste from operation are stored as LLW until radioactivity has decayed away and can be disposed of as ordinary trash, or until amounts are large enough for shipment to a LLW disposal site in containers (NRC, 2011c). In the study, I consider no disposal after storage, which is a conservative assumption since it reduce the quantities of waste being handling. Last, waste coming from the dismantling are directly disposed as either HLW, ILW or LLW.

Note: Numbers shown between brackets in Table 4.5 correspond to the waste flows represented by the dotted lines in Figure 4.3.

8 The NRC uses the term of spent nuclear fuel making the difference between spent *depleted* nuclear fuel and spent *used* nuclear fuel. In the study, spent nuclear fuel (or SNF) when cited alone should be understood as being the spent *used* nuclear fuel.

Phase	Parameter	Value	Unit	Source
(1) Mining	**Rock mined**	**1 058 000**	**t_{ROCK}/y**	
	Mining method	30%	open pit	Lenzen, 2008
		38%	ground excavation	Lenzen, 2008
		21%	in situ leaching	Lenzen, 2008
		11%	by-product of other mining	Lenzen, 2008
	Waste to ore ratio	9:1	Underground mining	US EPA, 2006
		3:1	Surface mining	US EPA, 2006
		7:1	(av.)	
	Recovery rate (yield)	94%		adapted from Lenzen, 2008
	Waste rock	**(916 000)**	**t_{ROCK}/y**	
	Ore recovered	**142 000**	**t_{ORE}/y**	
	Tailings	**(141 800)**	**t_{ORE}/y**	
	Ore grade	0.045%	U3O8 – Low (Australia)	Lenzen, 2008
		0.15%	U3O8 – baseline	Lenzen, 2008
		8%	U3O8 – High (Canada)	Lenzen, 2008
	Milling loss	0.5%		Lenzen, 2008
	Milling	**213**	**t_{U3O8}/y**	
		181	***t_U/y***	
	Tailings	**(1.1)**	**t_{U3O8}/y**	
	Conversion loss	0.5%		Lenzen, 2008
	Convers.	**266**	**t_{UF6}/y**	
		180	***t_U/y***	
	Tailings	**(1.3)**	**t_{UF6}/y**	

Table 4.5: Mass balance calculations of Case 1

Phase	Parameter	Value	Unit	Source
(2) Enriching	Feed assay	0.711%	U-235	Lenzen, 2008
	Product assay	3.5%	U-235	Lenzen, 2008
	Tails assay	0.25%	U-235	Lenzen, 2008
	Enrich. method	30%	Diffusion	Lenzen, 2008
		70%	Centrifuge	Lenzen, 2008
	Enrich. effort	120 000	SWU/y	Hore-Lacy, 2004
	Enrich.	**38**	**t_{UF6}/y (enriched)**	
		25	***t_U/y***	
	Depleted uranium	**(227)**	**t_{UF6}/y (depleted)**	
		(153)	***t_U/y***	
	Fab. loss	1%		Lenzen, 2008
	Fuel fab.	**28**	**t_{UO2}/y**	
		25	***t_U/y***	
	Tailings	**(0.4)**	**t_{UF6}/y**	
		(0.3)	***t_U/y***	

Table 4.5 (continued): Mass balance calculations of Case 1

Phase	Parameter	Value	Unit	Source
(3) Handling waste	Depleted uranium	227	t_{UF6}/y (depleted)	
	Spent used nuclear fuel	28	t_{USED}/y	
	Other waste from operation	13	t_{WASTE}/y	Lenzen, 2008
	Waste storage	**(256)**	**t_{HLW}/y**	
		(13)	**t_{LLW}/y**	
	Tailings	141 800	t_{ORE}/y	
		1	t_{U3O8}/y	
		1	t_{UF6}/y	
	Dismantling	10 000	t_{HLW}	Lenzen, 2008
		10 000	t_{ILW}	Lenzen, 2008
		100 000	t_{LLW}	Lenzen, 2008
	Lifetime	40	years	
	Waste disposal	**(300)**	**t_{HLW}/y**	
		(3 000)	**$t_{ILW/LLW}$/y**	
	Waste not sent to disposal	**13**	**t_{VLLW}/y**	
		(141 800)	**t_{ORE}/y**	

Table 4.5 (continued): Mass balance calculations of Case 1

4.4.2 Case 2: Nuclear energy (LWR power plant with reprocessing)

The protocol used for the mass balance evaluation of Case 2 is essentially the same as for Case 1. The only difference that here the production process also includes the fuel reprocessing phase as shown in Figure 4.4 which uses the same symbols as described in Case 1.

It shall be noted that Figure 4.4 is only a representation of the general circulation of material flows and does not necessarily represent the reality of such flows at the level of one power plant. Especially, one LWR burn either natural enriched uranium or reprocessed fuel but not both at the same time as the figure would suggest. Therefore, Figure 4.4 should be understood as the general functioning of the whole nuclear energy system including relations between the various internal parts of this system (reactors, enrichment methods, reprocessing methods, etc.).

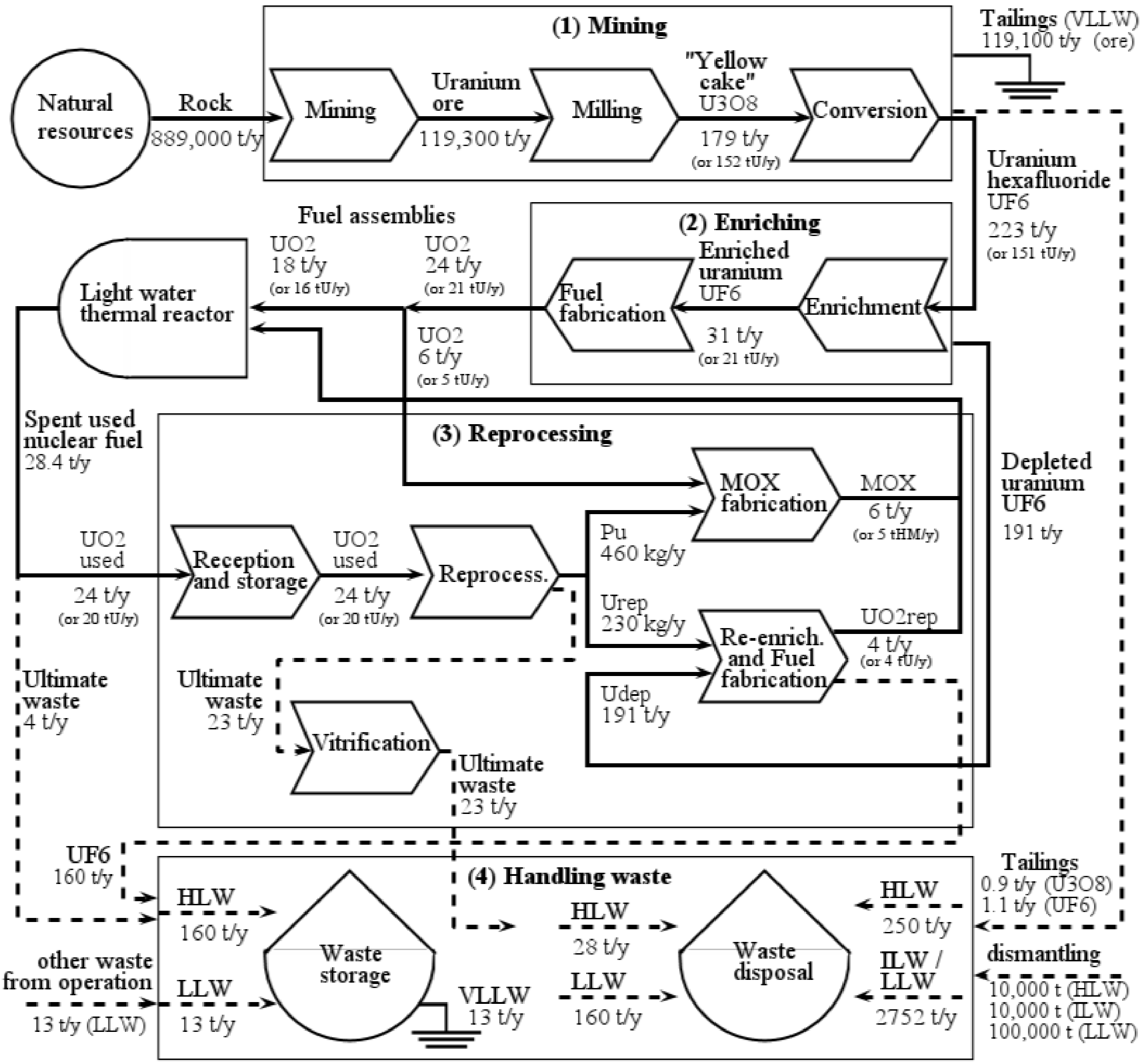

Figure 4.4: Mass balance of Case 2 (partly closed nuclear fuel cycle)

Table 4.6 presents the calculations of the material balance of Case 2. The specific aspects of this mass balance evaluation are detailed below:

- The presence of the reprocessing phase modifies the whole material balance of the system and especially the uranium enrichment process since less enriched uranium fuel is consumed in the system thanks to the recycling of part of the uranium and plutonium, the total heated material flow remaining the same between Cases 1 and 2 as explained in Section 4.2.3. In order to evaluate the mass balance for Case 2, several iterations have been necessary. Each iteration considers, first, the quantity of materials (uranium and plutonium) contained in both the used fuel (SNF) and the depleted uranium of Case 1. Second, the quantity of reprocessed fuels (MOX and UO2rep) that can be fabricated out of the recycled materials (Pu, Urep, and Udep) are evaluated. After iteration, it was found that the reprocessing phase implies a reduction of 16% of the flow of enriched natural uranium needed in the system (entering into the LWR), and ultimately of the natural uranium needed to be extracted. This result is in the same order of magnitude as the MIT study which evaluates a reduction of the enriched uranium fuel demand up to 25% (Kazimi et al., 2011).
- The mass balance for the enrichment process has been evaluated starting from the reduced value of enriched uranium product equal to $32t_{UF6}/y$ (in comparison with the $38t_{UF6}/y$ of Case 1). Then, the three other variables (feed assay, tail assay and enrichment effort) are evaluated using the same calculator as for Case 1 (WISE, 2009a). Results of the mass balance evaluation for the enrichment process are shown in Table A.2 of the appendixes.
- The mass balance of the reprocessing phase has been directly evaluated by using the calculator developed by the WISE Uranium Project (WISE, 2009b). The calculations of the mass balance for the reprocessing phase follow the same logic as for the enrichment process. As shown in Figure 4.5, all SNF materials (28t/y) are sent to the reprocessing plant which means that Case 2 represents the maximum reprocessing rate possible with the partly-closed nuclear fuel cycle. However, only 96% of the *fissile* materials can be recovered out of the SNF materials, meaning that almost all SNF materials are indeed sent to the storage and disposal facilities as ultimate waste.
- Results of the mass balance evaluation for each one of the three different processes (MOX fabrication, Urep and Udep re-enrichment) of the reprocessing phase are shown in Table A.3 of the appendixes.
    - Mixed oxide (MOX) fuel is a mixture of plutonium (with a given concentration of fissile plutonium, i.e. Pu-239 and Pu-241) and natural or depleted uranium. Here, I consider the MOX fuel as being a mix of plutonium and natural uranium (see Figure 4.4). Recycled uranium from depleted uranium (Udep) will rather be re-enriched in order to make reprocessed fuel (UO2rep) as explained below.
    - Udep is first re-enriched to natural assay, and then enriched further to fuel grade.
    - Urep is re-enriched to its initial enrichment equivalent, which is higher than the initial enrichment to compensate for the presence of impurities as explained earlier.

Phase	Parameter	Value	Unit	Source
(1) Mining	**Rock mined**	**889 000**	**t_{ROCK}/y**	
	Mining method	30%	open pit	Lenzen, 2008
		38%	ground excavation	Lenzen, 2008
		21%	in situ leaching	Lenzen, 2008
		11%	by-product of other mining	Lenzen, 2008
	Waste to ore ratio	9:1	Underground mining	US EPA, 2006
		3:1	Surface mining	US EPA, 2006
		7:1	(av.)	
	Recovery rate (yield)	94%		adapted from Lenzen, 2008
	Waste rock	**(770 000)**	**t_{ROCK}/y**	
	Ore recovered	**119 300**	**t_{ORE}/y**	
	Tailings	**(119 100)**	**t_{ORE}/y**	
	Ore grade	0.045%	U3O8 – Low (Australia)	Lenzen, 2008
		0.15%	U3O8 – baseline	Lenzen, 2008
		8%	U3O8 – High (Canada)	Lenzen, 2008
	Milling loss	0.5%		Lenzen, 2008
	Milling	**179**	**t_{U3O8}/y**	
		152	***t_U/y***	
	Tailings	**(0.9)**	**t_{U3O8}/y**	
	Conversion loss	0.5%		Lenzen, 2008
	Convers.	**223**	**t_{UF6}/y**	
		151	***t_U/y***	
	Tailings	**(1.1)**	**t_{UF6}/y**	

Table 4.6: Mass balance calculations of Case 2

Phase	Parameter	Value	Unit	Source
(2) Enriching	Feed assay	0.711%	U-235	Lenzen, 2008
	Product assay	3.5%	U-235	Lenzen, 2008
	Tails assay	0.25%	U-235	Lenzen, 2008
	Enrich. method	30%	Diffusion	Lenzen, 2008
		70%	Centrifuge	Lenzen, 2008
	Enrich. effort	**101 000**	SWU/y	
	Enrich.	**32**	**t_{UF6}/y (enriched)**	
		21	***t_U/y***	
	Depleted uranium	**(191)**	**t_{UF6}/y (depleted)**	
		(129)	***t_U/y***	
	Fab. loss	1%		Lenzen, 2008
	Fuel fab.	**24**	**t_{UO2}/y**	
		21	***t_U/y***	
	Tailings	**(0.3)**	**t_{UF6}/y**	
		(0.2)	***t_U/y***	

Table 4.6 (continued): Mass balance calculations of Case 2

Phase	Parameter	Value	Unit	Source
(3) Reprocess.	**SNF**	**28**	**t_{USED}/y**	
	Reprocess rate of SNF	100%	UO2 used	
	Compos. of SNF	95%	U-238	
		1%	U-235	
		2%	Pu	
		2%	fission prod. (waste)	
	Reception and storage	**24**	**t_{USED}/y**	
		20	***t_U/y***	
	SNF not reproc.	**(4)**	**t_{USED}/y**	
	Fissile material recovered	96%		
	Uranium recycled	**230**	**kg_{U-235}/y**	
	Plutonium recycled	**460**	**kg_{Pu}/y**	
	SNF not recovered	**(23)**	**t_{HLW}/y**	
	Uranium fuel consum.	6	t_{UO2}/y	
		5	*t_U/y*	
	Plutonium reproc. fuel fab.	**6**	**t_{MOX}/y**	
		5	***t_{HM}/y***	
	Uranium reproc. fuel fab.	**0.03**	**t_{UO2}/y**	
		0.03	***t_U/y***	
	Depleted uranium re-enrich.	**4**	**t_{UO2}/y**	
		4	***t_U/y***	

Table 4.6 (continued): Mass balance calculations of Case 2

Phase	Parameter	Value	Unit	Source
(4) Handling waste	Depleted uranium not recovered	160	t_{UF6}/y	
	SNF not reproc.	4	t_{USED}/y	
	Other waste from operation	13	t_{WASTE}/y	Lenzen, 2008
	Waste storage	**(160)**	**t_{HLW}/y**	
		13	**t_{LLW}/y**	
	Tailings	119 000	t_{ORE}/y	
		0.9	t_{U3O8}/y	
		1	t_{UF6}/y	
	Dismantling	10 000	t_{HLW}	Lenzen, 2008
		10 000	t_{ILW}	Lenzen, 2008
		100 000	t_{LLW}	Lenzen, 2008
	Lifetime	40	years	
	Waste disposal	**(270)**	**t_{HLW}/y**	
		(2 900)	**$t_{ILW/LLW}$/y**	
	Waste not sent to disposal	**(13)**	**t_{VLLW}/y**	
		(119 000)	**t_{ORE}/y**	

Table 4.6 (continued): Mass balance calculations of Case 2

4.4.3 Cases 3 and 4: Fossil energy

The material balance of the fossil energy system is much less complex than the one of the nuclear energy system. This is due to a whole process being more simple with less sub-processes, even when adding a CCS technology to the system, as shown in the example of Figure 4.5. The relative simplicity of the whole process with fossil energy already appears as an indicator of a better competitiveness since reducing the number of steps helps reducing the biophysical requirements for the making and maintenance of the flows and funds of the system.

Tables 4.7 and 4.8 present the calculations of the material balance of Case 3 and 4 respectively. These tables consider the following assumptions:

- The material balance of the fossil energy production process is only performed for the mining phase. Indeed, losses during the refining phase are considered as negligible as respect to the scope of this study, so that the annual consumption of coal for mining and refining is the same for the comparison.

- As explained in Section 4.2.4, the average heating value of coal (26 GJ/t) is evaluated based on the individual heating values of each type of coal resources from the 2007 MIT study on coal (Katzer et al., 2007) and distributed according to the share of each resource type in the coal mining market (U.S. EIA, 2010). As far as the share between underground mining (60%) and surface mining (40%) (WCI, 2009), those values will be used for the evaluation of the biophysical requirements of the fossil energy system.
- In Table 4.8, the carbon-capture efficiency of the CCS technology is considered equal to 90% as in the 2007 MIT study (Katzer et al., 2007) so that only 10% of the total direct CO2 emissions from the power plant remain released into the atmosphere after capture. Moreover, it is shown in the figure that the total amount of CO2 emitted by the power plant is not the same between Case 1 (2.7Mt_{CO2}/y) and Case 2 (3.3Mt_{CO2}/y). This is due to the CCS system of Case 2 which requires of a higher demand of coal in order to compensate the reduction of Rankine cycle efficiency (see Section 4.2.5).

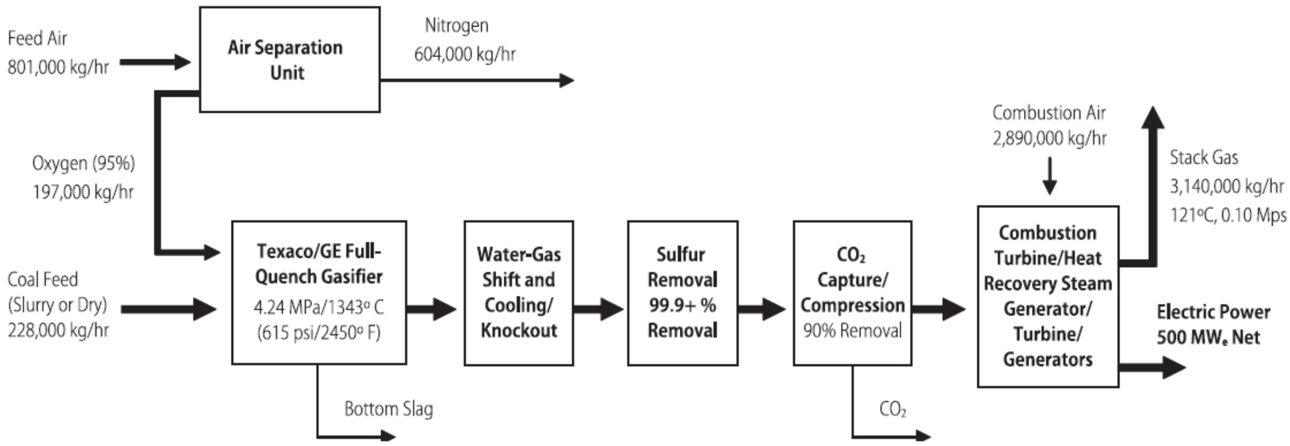

Figure 4.5: Example of a 500 MWe IGCC unit with CCS (source: Katzer et al., 2007)

Phase	Parameter	Value	Unit	Source
(1) Mining	Recov. Reserves	50%	Bituminous and anthracite	after US EIA, 2010
		32%	Sub-bit.	after US EIA, 2010
		18%	Lignite	after US EIA, 2010
	Heating value	30	GJ/t (Bit. and anth.)	Katzer et al., 2007
		25	GJ/t (Subbit.)	Katzer et al., 2007
		15	GJ/t (Lignite)	Katzer et al., 2007
		26	GJ/t (av.)	
	Mining method	40%	Surface mining	WCI, 2009
		60%	Underground mining	WCI, 2009
(3) Handling waste	CO2 captured	0	Mt_{CO2}/y	after Katzer et al., 2007
	CO2 emitted	2.7	Mt_{CO2}/y	after Katzer et al., 2007

Table 4.7: Mass balance calculations of Case 3

Phase	Parameter	Value	Unit	Source
(1) Mining	Recov. Reserves	50%	Bituminous and anthracite	after US EIA, 2010
		32%	Sub-bit.	after US EIA, 2010
		18%	Lignite	after US EIA, 2010
	Heating value	30	GJ/t (Bit. and anth.)	Katzer et al., 2007
		25	GJ/t (Subbit.)	Katzer et al., 2007
		15	GJ/t (Lignite)	Katzer et al., 2007
		26	GJ/t (av.)	
	Mining method	40%	Surface mining	WCI, 2009
		60%	Underground mining	WCI, 2009
(3) Handling waste	CO2 captured at 90% efficiency	3.0	$Mt_{captured}/y$	after Katzer et al., 2007
	CO2 emitted	0.3	$Mt_{emitted}/y$	after Katzer et al., 2007

Table 4.8: Mass balance calculations of Case 4

4.5 Evaluation of the biophysical requirements

The following sections present the comparison between the two fossil energy and nuclear energy production processes based on three biophysical requirements: electricity, fossil-fuels and labor. From those criteria, I expect to get a better understanding of the functioning of those two energy systems in their ability to supply (net) electricity to the rest of society. Then, an appraisal of the quality of nuclear energy system to deliver electricity will become possible and maybe lead to our objective of explaining the low economic competitiveness of nuclear energy using a biophysical explanation.

I focus the three different biophysical requirements detailed above for the phases that both nuclear energy and fossil energy have in common: (i) mining; (ii) refining/enriching; (iii) generating electricity (power plant); (iv) handling pollution/radioactive wastes.

It shall be noted that transportation requirements have not been considered in the study. Although fossil energy implies a very large amount of materials to be transported, the distances remain relatively short since the mines are generally in the same area as the power plants (regional scale). The nuclear energy process exactly is the opposite as relatively few quantities of fuel materials have to be transported every year to the nuclear plant. However, in the case of the nuclear fuel cycle, the low amount of fuel to be transported is compensated by large distances (international scale). For instance, natural uranium can be sent from a mine in Australia to an enrichment facility in France and then re-sent in the form of nuclear fuel to the plants disseminated all over the world. Proximity is not a criteria of choice within the nuclear energy system given the relatively low cost of transportation (low quantities) in comparison with other capital costs involved during the process. Moreover, transportation is not limited to the flows (fuel) but is also necessary during the making and maintenance of the funds (construction, dismantling of the various facilities) which are more numerous in the nuclear fuel cycle. In conclusion, the assumption of not considering transportation in the study probably does not advantage fossil energy nor nuclear energy.

In addition, only the dismantlement of radioactive materials has been considered in the study (nuclear energy system). Indeed, not including the biophysical requirements for dismantling the IGCC power plant and other facilities of the fossil energy process would be compensated by the efforts necessary for dismantling the front-end and back-end facilities of the nuclear energy process.

4.5.1 Electricity requirements and net electricity generated

The requirements for the nuclear energy systems are evaluated using Lenzen's (2008) study. Since no data have been found on the electricity and fossil-fuel requirements of the reprocessing phase of Case 2, the following assumptions have been considered in the study:

- The reception and storage process is considered having the same requirements as the waste storage from the (5) Handling waste phase.
- The reprocessing and the vitrification processes are considered having the same requirements as the operation process from the (3) Power plant phase.
- The MOX and UO2 fuel fabrication processes are considered having the same requirements as the fuel fabrication process from the (2) Enriching phase.
- The Urep and Udep re-enrichment process has the same requirements as the enrichment process of the (2) Enriching phase (same facilities).

For the fossil energy system without CCS technology (Case 3), the electricity requirements are considered negligible, while electricity is required for the compression, transportation and injection (Koornneef et al., 2008) of the carbon captured by the CCS technology (Case 4).

Table 4.9 presents the net electricity generated by each system which can directly be derived from the tables of Appendix B presenting detailed results of the electricity requirement evaluation. Then, the electricity requirements (input) can be compared to the net electricity generated as presented in Table 4.10 which shows the specific electricity requirements for all four cases of the study.

Nuclear energy			
Case 1		**Case 2**	
Electricity output	9000 GWh_{el}/y	Electricity output	9000 GWh_{el}/y
Electricity input	300 GWh_{el}/y	Electricity input	300 GWh_{el}/y
Net electricity generated	**8700 GWh_{el}/y**	**Net electricity generated**	**8700 GWh_{el}/y**

Fossil energy			
Case 3		**Case 4**	
Electricity output	3300 GWh_{el}/y	Electricity output	3300 GWh_{el}/y
Electricity input	0 GWh_{el}/y	Electricity input	400 GWh_{el}/y
Net electricity generated	**3300 GWh_{el}/y**	**Net electricity generated**	**2900 GWh_{el}/y**

Table 4.9: Net electricity generated (Cases 1 to 4)

Nuclear energy

Case 1

(1) Mining	Mining, Milling and Conversion	*Electricity requirement negligible*
(2) Enriching	Enriching and Fuel fabrication	0.01 MWh_{el}/MWh_{el}
(3) Power plant	Construct.	*Electricity requirement negligible*
	Operation	0.001 MWh_{el}/MWh_{el}
(4) Handling waste	Waste storage and Waste disposal	0.02 MWh_{el}/MWh_{el}
TOTAL		**0.03 MWh_{el}/MWh_{el}**

Case 2

(1) Mining	Mining, Milling and Conversion	*Electricity requirement negligible*
(2) Enriching	Enriching and Fuel fabrication	0.01 MWh_{el}/MWh_{el}
(3) Power plant	Construct.	*Electricity requirement negligible*
	Operation	0.001 MWh_{el}/MWh_{el}
(4) Reprocess.	Reception and storage	*Electricity requirement negligible*
	Reprocess.	0.001 MWh_{el}/MWh_{el}
	Fuel fab. and Vitrification	0.002 MWh_{el}/MWh_{el}
(5) Handling waste	Waste storage and Waste disposal	0.02 MWh_{el}/MWh_{el}
TOTAL		**0.03 MWh_{el}/MWh_{el}**

Fossil energy

Case 3

(1) Mining	Mining	*Electricity requirement negligible*
(2) Cleaning	Sulfur removal	*N/A*
(3) Handling waste		*N/A*
TOTAL		**0 MWh_{el}/MWh_{el}**

Case 4

(1) Mining	Mining	*Electricity requirement negligible*
(2) Cleaning	Sulfur removal	*Electricity requirement negligible*
(3) Handling waste	Capture, Compress., transport and storage	0.1 MWh_{el}/MWh_{el}
TOTAL		**0.1 MWh_{el}/MWh_{el}**

Table 4.10: Specific electricity requirements (Cases 1 to 4)

4.5.2 Direct and indirect fossil-fuel requirements

For the nuclear energy system (Cases 1 and 2), there is no direct fossil-fuel requirements as the nature of the nuclear fuel (uranium) is mineral, not fossil. Therefore, only indirect fossil-fuel (oil) requirements are necessary in the whole process. Those requirements for the nuclear energy systems are evaluated using Lenzen's (2008) study. For the reprocessing phase of Case 2, the same assumptions described in Section 4.4.1 are considered for the fossil-fuel requirement evaluation.

Table 4.11 presents the specific oil requirements for all four cases of the study. Detailed results of the fossil-fuel requirement evaluation are presented in Appendix C.

For the fossil energy system (Cases 3 and 4), direct fossil-fuel (coal) requirements must be differentiated from the indirect fossil-fuel (oil) requirements. The direct fossil-fuel requirements correspond to the coal demand of the power plant, while indirect fossil-fuel requirements correspond to the oil consumed in the whole process as in the nuclear energy system. Then, coal and oil requirements of the fossil energy system are aggregated and expressed in terms of toe in order to compare the fossil energy with nuclear energy. It shall be mentioned that this aggregation does not correspond to the reductionism in energy analysis which consists in expressing different PES in one single unit (joule, kWh, etc.) showing a misunderstanding of the energetic aspects of PES which therefore should remain expressed in biophysical units (tons, liters, etc.) in any energy analysis. Here, the aggregation of oil and coal requirements does not deal with energetics as it is only to compare the total fossil-fuel requirements of the nuclear energy and fossil energy systems. Such aggregation is made possible because coal and oil—being both fossil fuels—are both producing heat (same energy form) when consumed. As a matter of fact, this is possible to use an equivalent ratio to express coal (tce) in terms of tons of oil equivalent (toe). The coal-to-oil conversion ratio considered in the study has been evaluated by comparing the heating values of oil (43.38GJ/toe from OECD/IEA, 2005) and coal (26GJ/tce, discussed in Section 4.2.4) leading to a ratio equal to 0.592toe/tce.

Table 4.12 presents the specific direct and indirect fossil-fuel requirements for all four cases of the study.

Nuclear energy

Case 1

(1) Mining	Mining, Milling and Conversion	1.5 toe/GWh$_{el}$
(2) Enriching	Enriching and Fuel fabrication	0.1 toe/GWh$_{el}$
(3) Power plant	Construct.	0.7 toe/GWh$_{el}$
	Operation	3.2 toe/GWh$_{el}$
(4) Handling waste	Dismantling	0.3 toe/GWh$_{el}$
	Waste storage and Waste disposal	1.9 toe/GWh$_{el}$
TOTAL		**7.7 toe/GWh$_{el}$**

Case 2

(1) Mining	Mining, Milling and Conversion	1.3 toe/GWh$_{el}$
(2) Enriching	Enriching and Fuel fabrication	0.1 toe/GWh$_{el}$
(3) Power plant	Construct.	0.7 toe/GWh$_{el}$
	Operation	3.2 toe/GWh$_{el}$
(4) Reprocess.	Reception and storage	0.1 toe/GWh$_{el}$
	Reprocess.	3.2 toe/GWh$_{el}$
	Fuel fab. and Vitrification	3.2 toe/GWh$_{el}$
(5) Handling waste	Dismantling	0.3 toe/GWh$_{el}$
	Waste storage and Waste disposal	1.3 toe/GWh$_{el}$
TOTAL		**13.4 toe/GWh$_{el}$**

Fossil energy

Case 3

(1) Mining	Mining		2.9 toe/GWh$_{el}$
(2) Cleaning	Sulfur removal	*Oil requirement negligible*	
(3) Handling waste		*N/A*	
TOTAL			**2.9 toe/GWh$_{el}$**

Case 4

(1) Mining	Mining		2.9 toe/GWh$_{el}$
(2) Cleaning	Sulfur removal	*Oil requirement negligible*	
(3) Handling waste	Capture, Compress., transport and storage	*Oil requirement negligible*	
TOTAL			**2.9 toe/GWh$_{el}$**

Table 4.11: Specific indirect fossil-fuel (oil) requirements (Cases 1 to 4)

Nuclear energy

Case 1

(1) Mining	Mining, Milling and Conversion	1.5 toe/GWh$_{el}$
(2) Enriching	Enriching and Fuel fabrication	0.1 toe/GWh$_{el}$
(3) Power plant	Construct.	0.7 toe/GWh$_{el}$
	Operation	3.2 toe/GWh$_{el}$
(4) Handling waste	Dismantling	0.3 toe/GWh$_{el}$
	Waste storage and Waste disposal	1.9 toe/GWh$_{el}$
TOTAL		**7.7 toe/GWh$_{el}$**

Case 2

(1) Mining	Mining, Milling and Conversion	1.3 toe/GWh$_{el}$
(2) Enriching	Enriching and Fuel fabrication	0.1 toe/GWh$_{el}$
(3) Power plant	Construct.	0.7 toe/GWh$_{el}$
	Operation	3.2 toe/GWh$_{el}$
(4) Reprocess.	Reception and storage	0.1 toe/GWh$_{el}$
	Reprocess.	3.2 toe/GWh$_{el}$
	Fuel fab. and Vitrification	3.2 toe/GWh$_{el}$
(5) Handling waste	Dismantling	0.3 toe/GWh$_{el}$
	Waste storage and Waste disposal	1.3 toe/GWh$_{el}$
TOTAL		**13.4 toe/GWh$_{el}$**

Fossil energy

Case 3

(1) Mining	Mining	220 toe/GWh$_{el}$
(2) Cleaning	Sulfur removal	*Fossil-fuel requirement negligible*
(3) Handling waste		*N/A*
TOTAL		**220 toe/GWh$_{el}$**

Case 4

(1) Mining	Mining	310 toe/GWh$_{el}$
(2) Cleaning	Sulfur removal	*Fossil-fuel requirement negligible*
(3) Handling waste	Capture, Compress., transport and storage	*Fossil-fuel requirement negligible*
TOTAL		**310 toe/GWh$_{el}$**

Table 4.12: Specific direct and indirect fossil-fuel requirements (Cases 1 to 4)

4.5.3 Direct and indirect CO2 emissions

CO2 emissions are directly derived from the direct and indirect fossil-fuel requirements presented in appendix C. Direct CO2 emissions only concern the fossil energy system for which the emissions are known from Tables 4.7 and 4.8. Indirect CO2 emissions are evaluated considering the oil requirements of both systems and an average oil-to-CO2-emission conversion ratio (3.4t_{CO2}/toe). Detailed results of the CO2-emission evaluation are presented in Appendix D.

The study uses the CO2-equivalent of burning oil and coal. This does not include any economic aspects so it should not to be confused with the economy wide GHG intensity we can find in the literature, which corresponds to the CO2-equivalent released when burning 1toe or 1tce.

Table 4.13 presents the specific CO2 emissions for all four cases of the study.

Nuclear energy

Case 1			Case 2		
Direct emissions	Power plant operation	11 t_{CO2}/GWh_{el}	Direct emissions	Power plant operation	11 t_{CO2}/GWh_{el}
Indirect emissions	Fuel cycle process	16 t_{CO2}/GWh_{el}	Indirect emissions	Fuel cycle process	35 t_{CO2}/GWh_{el}
TOTAL		**26 t_{CO2}/GWh_{el}**	**TOTAL**		**46 t_{CO2}/GWh_{el}**

Fossil energy

Case 3			Case 4		
Direct emissions	Power plant operation	830 t_{CO2}/GWh_{el}	Direct emissions	Power plant operation	120 t_{CO2}/GWh_{el}
Indirect emissions	Fuel cycle process	10 t_{CO2}/GWh_{el}	Indirect emissions	Fuel cycle process	10 t_{CO2}/GWh_{el}
TOTAL		**840 t_{CO2}/GWh_{el}**	**TOTAL**		**130 t_{CO2}/GWh_{el}**

Table 4.13: Specific CO2 emissions (Cases 1 to 4)

4.5.4 Labor requirements

Labor is also a biophysical requirement for any energy process. Labor requirements are difficult to evaluate for the nuclear energy system given the broad range of scale involved with its whole process both in space and time which make difficult to identify what the real needs are for a given baseline case at a given time. This problem is acknowledged by the IAEA saying that "data are scarce on the number of people today with the various skills needed in the nuclear industry" (OECD/IAEA, 2010).

In order to overcome this problem, I consider one specific approach for each one of the different phases of Cases 1 and 2 as follows:

- Labor productivity of mining phase has been evaluated based on the different countries for which both annual employment, production and average grade were provided (OECD/IAEA, 2004). Based on Table E-1 of Appendix E presenting details of the labor requirement evaluation, an average productivity of 80t_{ORE}/man-year has been obtained. Note that the uranium mining productivity cannot directly be compared with the coal mining productivity because the amount of uranium ore needed to be mined is much higher than the nuclear fuel that will be fabricated out of the ore (see Figure 4.3).

- Labor requirements for the enriching phase have been derived from Rothwell's work on uranium enrichment (Rothwell, 2009) and nuclear fuel fabrication (Rothwell, 2010) which provides results per unit of materials.
- Labor requirements for the power plant related processes (operation and construction) have been found in NEI, 2010. On that respect, it shall be mentioned that no R&D efforts are considered in this study although each power plant involves between 5 and 10 years of dedicated design efforts before its licensing.
- Labor requirements for dismantling the power plant are also difficult to evaluate. Indeed, the experience of the first dismantlements around the world has shown high variations in terms of the financial costs (Lenzen, 2008) that exceed in some cases the costs of construction of the facility, and so it is the case for labor requirements. In the study, I considered an average dismantling cost of about 45% of the construction cost.
- Labor requirements for handling the waste are evaluated considering the case of France where employment at the ANDRA—the French agency in charge of waste management—allows us to isolate labor requirements distributed in terms of waste categories (HLW, ILW and LLW).
- For Case 4, labor requirements for reprocessing are based on the French experience of La Hague site. Although, this site includes both a waste disposal and a waste reprocessing plant, I considered in this study that the HLW waste being reprocessed at La Hague would have to be managed at some point—be it postponed in the future. As a result, labor allocated to waste reprocessing in the study already take implicitly into account labor requirements for handling HLW waste.
- In order to express the labor requirements in terms of hours, 1,800 annual working hours have been considered which correspond to the average value in the OECD countries (OECD, 2008).

As far as the fossil energy system, labor requirements are only considered for the mining process, the other ones being negligible.

Table 4.14 presents the specific labor requirements for all four cases of the study.

Nuclear energy

Case 1			Case 2		
(1) Mining	Mining, Milling and Conversion	367 h/GWh_{el}	(1) Mining	Mining, Milling and Conversion	309 h/GWh_{el}
(2) Enriching	Enriching and Fuel fabrication	25 h/GWh_{el}	(2) Enriching	Enriching and Fuel fabrication	21 h/GWh_{el}
(3) Power plant	Construct.	97 h/GWh_{el}	(3) Power plant	Construct.	97 h/GWh_{el}
	Operation	83 h/GWh_{el}		Operation	83 h/GWh_{el}
(4) Handling waste	Dismantling	43 h/GWh_{el}	(4) Reprocess.	Reception and storage Reprocess. Fuel fab. and Vitrification	17 h/GWh_{el}
	Waste storage and Waste disposal	3 h/GWh_{el}	(5) Handling waste	Dismantling	43 h/GWh_{el}
TOTAL		**620 h/GWh_{el}**		Waste storage and Waste disposal	3 h/GWh_{el}
			TOTAL		**570 h/GWh_{el}**

Fossil energy

Case 3				Case 4			
(1) Mining	Mining		50 h/GWh_{el}	(1) Mining	Mining		60 h/GWh_{el}
(2) Cleaning	Sulfur removal	*Labor requirement negligible*		(2) Cleaning	Sulfur removal	*Labor requirement negligible*	
(3) Handling waste		*N/A*		(3) Handling waste	Capture, Compress., transport and storage	*Labor requirement negligible*	
TOTAL			**50 h/GWh_{el}**	**TOTAL**			**60 h/GWh_{el}**

Table 4.14: Specific labor requirements (Cases 1 to 4)

4.6 Sensitivity analysis

The results shown in the previous section can vary widely because of different factors. Indeed, it has been shown that the ore grade and the enrichment method are the most important influencing parameters (Lenzen, 2008) for the nuclear energy system, while the mining method (surface vs. underground) appears to be a key factor given the difference of productivity between those two methods (Darmstadter, 1999).

As a result, three other calculations are performed in this sensitivity analysis considering the following scenarios:

1. A low value of uranium ore grade (0.045%) which represents the essential of the reserves in Australia (sensitivity analysis on Cases 1 and 2).
   There is a high variation of the uranium ore grades between the different mines around the world as shown by Lenzen (2008). The importance of the resource

quality in the quality of energy sources has been demonstrated a long time ago in the case of fossil energy sources. Indeed, "the average grade mined also is very sensitive to the mining rate, and the mean grade declines substantially when the rate of extraction increases for society" (Hall et al. 1986). However, as correctly noticed by Hall (2008a), there has been little work done on the influence on the quality of nuclear energy production process due to the decreasing quality of uranium ore, which will be used when either uranium increases in price or high quality deposits become scarce. Even the MIT study on the nuclear fuel cycle (Kazimi et al., 2011) does not discuss this issue, while it is discussed in the other MIT study about coal (Katzer et al., 2007). On that respect, Lenzen (2008) refers to the work of Storm van Leeuwen and Smith ([30] in Lenzen, 2008) who have studied the relationship between natural resource quality (uranium ore grade) and energy intensity. According to their study, this relationship is exponential meaning that energy intensity increases more rapidly than ore grade decreases, the energy intensity being inversely proportional to the recovery rate as shown in Figure A.1. The authors also showed that the empirical extraction yield declines much more sharply than the hypothetical one. Figure 4.6 illustrates the increase in fossil-fuel requirements due to the variations of uranium ore grades.

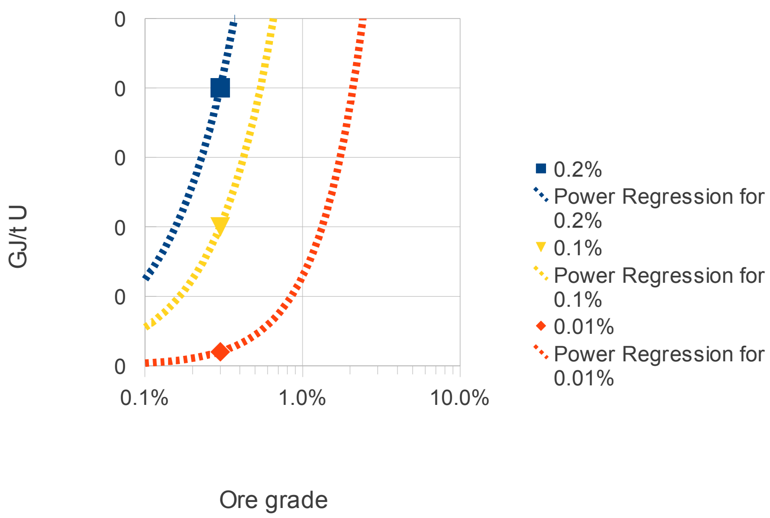

Figure 4.6: Specific fossil-fuel requirements for mining and milling vs. ore grade (source: after Lenzen, 2008)

The baseline cases of this study consider an average ore grade of 0.15%. Given the sharp variation shown in Figure 4.6, one can expect large variations on the biophysical requirements. This variation in the ore grade is a source of high uncertainties in the evaluation of any analysis dealing with the nuclear fuel cycle.

2. All enrichment using the gas centrifuge method (100%) which requires less electricity than the gaseous diffusion method.

In the study, 30% of the enrichment uses gaseous diffusion. However, this percentage is decreasing in favor of the centrifuge method which justifies the scenario considered in the sensitivity analysis.

3. All coal mining using the surface method (100%) which entails a higher productivity than the underground mining method.
In the study, only 40% of the mining is performed at the surface. However, the trend is to develop this type of mining method especially in developed countries such as in Germany. This scenario represents the hypothetical case when all coal mining would be performed at the surface.

Table 4.15 presents the results of the sensitivity analysis.

Variable	Scenario	Variation	Case	Electricity requ. (MWh_{el}/MWh_{el})		Fossil-fuel requ. (toe/GWh_{el})		CO2 emissions (t_{CO2}/GWh_{el})		Labor requ. (h/GWh_{el})	
				Value	*(Sensi-tivity)*		*(Sensi-tivity)*		*(Sensi-tivity)*		*(Sensi-tivity)*
	Baseline cases		Case 1	0.03		7.7		26		620	
			Case 2	0.03		13.4		46		570	
			Case 3	*negligible*		220		840		50	
			Case 4	0.1		310		130		60	
Ore grade	Low (Australia)	0.045%	Case 1	0.03	*(0%)*	**10.0**	***(30%)***	**34**	***(30%)***	**1470**	***(140%)***
			Case 2	0.03	*(0%)*	**15.3**	***(10%)***	**52**	***(10%)***	**1290**	***(130%)***
Enrichment method	100% Centrifuge	1	Case 1	**0.02**	***-(20%)***	7.6	*(0%)*	26	*(0%)*	610	*(0%)*
			Case 2	**0.02**	***-(20%)***	13.3	*(0%)*	45	*(0%)*	570	*(0%)*
Mining method	100% Surface	1	Case 3	*negligible*	*N/A*	219	*(0%)*	832	*(0%)*	**30**	***-(40%)***
			Case 4	0.1	*(0%)*	300	*(0%)*	124	*(0%)*	**40**	***-(30%)***

Table 4.15: Results of the sensitivity analysis

5. DISCUSSION OF THE RESULTS

5.1 Net energy (electricity) generated

As discussed in Section 2, an energetically coherent evaluation of the net energy of both nuclear and fossil energy systems in the production of electricity can only consider the electricity input needed through the each whole process. As a matter of facts, the output/input ratios (or EROI) of the nuclear energy system is relatively high (about 30:1, from Table 4.9) and higher than for the fossil energy system including a CCS system (about 8:1). Nevertheless, this does not mean that nuclear energy is "better" for society than fossil energy at producing electricity since there are other biophysical considerations that enter into the discussion.

This illustrates the limits of net energy analyses when dealing with energy systems for the production of electricity (EC) which energy form is very different from the PES entering its process. In more general terms, it also illustrates the limits of using a one-dimensional analysis when carrying out a comparison of different energy systems, and the need for a more holistic adoption of multi-criteria analyses, as discussed in Section 2.1.

5.2 Oil dependency of nuclear energy

From the study, we see that nuclear energy is requiring more than twice as much oil as fossil energy (7.7toe/GWh_{el} vs. 2.9toe/GWh_{el}, from Table 4.11)—which becomes close to 5 times more when adding the reprocessing phase to the nuclear energy system (13.4toe/GWh_{el}). It demonstrates that nuclear energy is much more dependent on oil than fossil energy.

As a result, the oil dependency of nuclear energy represents a major limitation to this option in the discussion about alternative energy sources which main objective especially is to break the dependence on oil—as well as reducing the carbon footprint—of the society.

5.3 Limits of nuclear energy as a carbon-free alternative

By definition, fossil energy sources are dependent on fossil-fuel resources. As a consequence, the total (direct and indirect) fossil-fuel requirements of the fossil energy system are much higher than for the nuclear energy system (220–310toe/GWh_{el} vs. 7.7–13.4toe/GWh_{el}, from Table 4.12). However, in terms of CO2 emissions, they are also significant for nuclear energy—representing between 20% (Case 1 in Table 4.13) and 35% (Case 2) of the total emissions of fossil energy with carbon capture (Case 4). To make things even worse, those ratios become higher (26% and 42% respectively, from Table 4.15) when considering variations in the ore quality of uranium resources. This clearly demonstrates that the nuclear energy system as a whole is not a carbon-free energy source contrary to popular believes. As a matter of facts, the relevance of CO2 emissions of the nuclear energy sector should be considered more deeply in those discussions.

Yet there is another problem with the CO2 emissions of nuclear energy. Indeed, Table 4.11 shows that 30% of the indirect fossil-fuel requirements come from the front-end process—before the power plant has generated any kWh of electricity—and so does the CO2 emitted by the whole process. This fact becomes significant when discussing any energy scenario such as it is the case with the IAEA's (2009) growth scenario which expects the worldwide electricity generation being doubled by 2030 compared to 2008, where nuclear energy would contribute to 18% of this growth (electricity generation increasing by about 6% per year). In that case of a rapid expansion of the nuclear energy sector, using our evaluation of the average annual CO2 emissions is not possible because this method of analysis does not catch the dynamics of the emissions. This problem of large CO2 emissions that need to be "invested" before actually benefiting from the electricity generated by the nuclear power plant is the same problem as the large up-front capital costs required for this energy system to exist and which limit its expansion.

The general dynamics of energy (electricity) generation of the nuclear energy system is illustrated in Figure 5.1. It shows that the rapid deployment of any energy system actually creates a need for energy from existing power plants which is called *energy cannibalism* (Pearce, 2008). This corresponds to accumulating energy costs (or CO2 emissions) from successive construction phases before having any energy production, leading to an overall energy need during a significant period of time during which there is no net energy generation.

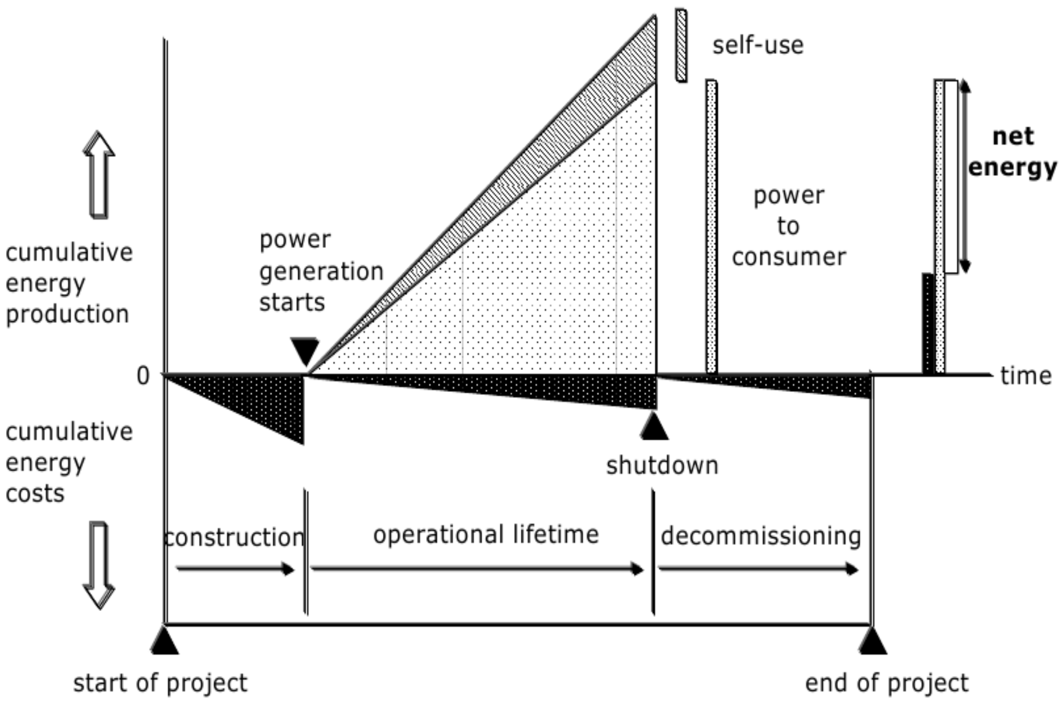

Figure 5.1: General dynamics of the nuclear energy system

Coming back to the problems entailed by a rapid expansion of the electricity sector, if any prediction is not possible, still we can see from the above discussion that, if the growth scenario proposed by the IAEA (2009) was to be applied, the overall CO2 emissions coming from the worldwide electricity generation might indeed not be reduced. In fact, it sounds difficult that renewable energy sources alone could contribute to the other 82% of the growth envisioned (assuming that nuclear energy contributes to the first 18% as indicated before), so that in reality this scenario still rely on some contribution from the fossil energy sector to fill the gap. Then, the problem is that the CCS technology is most probably not to be available at a large scale before 2030, so that such an energy scenario cannot lead to a low-carbon economy.

5.4 The reprocessing non-sense

From Section 4.4.2, we see that the quantity of reprocessed uranium (Urep) coming from the reactor is negligible in comparison to the quantities of depleted uranium (Udep) coming from the enrichment process (see Figure 4.4). This means that reprocessing spent used nuclear fuel (SNF) does not make much sense on the uranium side. As a matter of facts, the very motivation for reprocessing SNF materials appears to be a way to "recycle"[9] the plutonium (Pu) produced in the LWR, so for proliferation concerns rather than for uranium stock depletion considerations. But even the proliferation concerns are not fully solved when looking at the dynamics of the reprocessing phase. Indeed, according to the MIT study on the nuclear fuel cycle, the SNF can only be reprocessed one or two times (Kazimi et al., 2011). This is due to impurities (U-236, a neutron absorber) produced during the fission reactions in the reactor and then found in the SNF materials (WISE, 2009b). It implies that the re-enrichment of Urep must be higher than its initial enrichment of natural uranium to compensate the presence of those impurities, as explained in Section 4.4.2. As a consequence, since the presence of impurities increases with the number of reprocessing cycles, in practice, it becomes simply not economically viable to keep reprocessing SNF (at least from the payer's side, not from the reprocessing provider's side) because it would entail much more separative work than for natural uranium enrichment for making the same quantity of fuel. The Case 2 described in this study—being a *static* case—does not catch this *dynamic* effect related to the existence of a limited number of reprocessing cycles. As a result, the 16% reduction of uranium fuel consumption found in this study is not realistic—and so does the 25% maximum reduction evaluated by the MIT study. Therefore, the partly-closed nuclear fuel cycle—as described in this study—does not appear to be a reasonable option on all security, economical and environmental aspects at once. The strategy of using the reprocessing seems to be driven by other motives—be they are political ones.

The current application of the partly-closed nuclear fuel cycle was supposed to be only a temporary step before reaching the complete development of the full-closed cycle by the use of fast neutron reactors (Mayumi and Polimeni, 2011) that have the possibility of consuming the plutonium produced in thermal neutron reactors. The idea was that only few conventional thermal reactors would have been necessary in order to feed a large fleet of fast neutron reactors (or breeder reactors) which have the advantage of producing more fuel than they consume. The problem is that since natural uranium resources are not facing depletion, the price of uranium (flow) has remained relatively low up to now (Dittmar, 2011b) in comparison with the high capital costs for making and maintaining the funds. This low price of uranium has finally led to the reverse situation of what was initially planned: a large fleet of thermal reactors have been deployed while only very few experimental fast neutrons reactors have been developed. And as long as uranium will remain relatively cheap, there is no (economic) reason for this to change.

9 Given the dynamically limited reprocessing phase discussed here, the notion of "recycling" should be used with caution in the case of the partly-closed nuclear fuel cycle, as it leads to think that SNF reprocessing is a *closed loop*, which clearly is not the case as this study demonstrates.

On that respect, there are divergent views about uranium reserves. The MIT study on the nuclear fuel cycle—which also criticizes the partly-closed nuclear fuel cycle—claims that uranium resources are sufficient to feed a growth in the consumption of electricity until the end of the 21st century at current consumption rate (Kazimi et al., 2011). But, this study does not discuss the quality or natural uranium ores which has been shown here as being one of the most sensible variables so it represents a fundamental aspect that should be taken into account in studies. Even other studies that do not necessarily take into account the variation of ore quality contradict the conclusions of the MIT. According to two recent studies (Dittmar, 2011b; Mayumi and Polimeni, 2011) uranium reserves might not end up being sufficient to feed the scenario of growth considered by the MIT. Indeed, while Mayumi and Polimeni indicate that uranium reserves would not be able to feed the current worldwide electricity consumption, Dittmar claim that they would not even be sufficient to fuel the existing and planned nuclear power plants during the next 10–20 years.

6. FURTHER DISCUSSIONS

6.1 Things are not clear with nuclear energy

The results of the study presented in Section 4 and discussed in the previous sections show that high uncertainty affects the nuclear energy system. This is due to the non-linearity between the metabolic pattern of the system and different variables such as the resource quality. Such a non-linearity represents the limits of using a *static* model (with annually averaged values) when analyzing the nuclear energy system because such a model does not consider the *dynamic* effects over time, as discussed in the next sections. As a matter of facts, the linear model of annual biophysical requirements presented here does not provide a full understanding of the behavior of the nuclear energy system. Indeed, fossil and nuclear fuel cycles are embedded into a certain time scale which must be in the same order of magnitude of one year in order to give meaning to annually averaged values. The next section provides a comparison of the time scales of fossil energy and nuclear energy.

Another problem adding uncertainty to the competitiveness of nuclear energy is the specific complexity of its whole production process deployed—by essence—at *large scale* (Diaz Maurin, 2011b). For instance, this complexity entails (1) problems of labor productivity which reduces the possibility of standardization of the production process; and (2) problems of energy requirement efficiency.

6.2 The issue of time scale

The time scale at which one energy system operates is related to its speed, i.e. its ability to integrate changes more or less rapidly. Before making a comparison between fossil energy and nuclear energy, any quantification and representation of a system implying changes in speed requires a pre-analytical definition of a space-time scale for the domain used to describe changes in speed that defines: (i) the time differential (*grain*)—the time necessary to produce the output from the input within the process—in relation to (ii) the time domain of the analysis (*extent*) (Giampietro et al., 2011b)[10]. Using Georgescu-Roegen's (1971) flow-fund theoretical model, the grain are related to the generation and consumption of *flows*—elements disappearing and/or appearing over the duration of the representation—while the extend is related to the reproduction of *funds*—agents that are responsible for energy transformations and are able to preserve their identity over the duration of the representation.

The main problem when discussing the issue of (space-)time scale is that there is not only one possible representation of the speed of an energy system. Indeed, since a representation depends on the perception of the observer, several representations can all be valid. Now, beyond being valid, it must be checked the relevance of a given representation for the issue at stake by looking at: (i) what is missing in this representation; and (ii) what are the causal effects on the numbers.

Two different representations can be considered when discussing the speed of the nuclear energy system depending on which output we focus on—being either electricity (see Figures 4.1 and 4.2) or waste (see Figures 4.3 and 4.4)—that are both flows generated by the system. That way, when considering an electricity-oriented representation of the speed of the nuclear energy system, the time domain can be limited

10 Here, I focus only on the issue of *time* letting alone the *space* dimension.

to the lifetime of the power plant—including its related R&D, construction, operation and dismantling phases though—leading to an extent equal to 60–65 years, as shown in Table 6.1. Then, when considering a waste-oriented representation, the time domain should now include the phases related to the handling of waste. However, given the very long time involved in those phases, they can no longer be considered as flow elements (the speed of changes being too low to meter) so that they become fund elements and thus are included in the time domain evaluation, as shown in Table 6.1. A strict waste-oriented representation would therefore have to consider an extent equal to about 10^5 years corresponding to the very long time necessary for waste disposal.

When compared to the time domain within which the fossil energy system operates, even when ignoring waste handling phase (representation #1), the time domain necessary to consider for the representation of the nuclear energy system is twice as much longer as the one of fossil energy system. This is of particular importance because the longer the time of representation, the more difficult the appraisal of the system involved. In addition, while the behavior of the fossil energy system can be captured considering a reasonable time frame of about 30 years—corresponding more or less to one labor generation—capturing the behavior of the nuclear energy system requires two labor generations making the assessment even more difficult as it involves a necessary very long term perspective.

Phase	Nuclear energy		Fossil energy
	Representation #1 (electricity-oriented)	Representation #2 (waste-oriented)	
R&D and licensing	~ 10 y	~ 10 y	< 1 y
Construction	~ 5 y[(a)]	~ 5 y[(a)]	~ 3 y
Plant lifetime	35–40 y	35–40 y	30 y
Dismantling	~ 10 y	~ 10 y	< 1 y
Waste storage	–	10–30 y	N/A
Reprocessing	–	8–15 y	N/A
Waste disposal	–	~ 10^5 y	N/A
Extent	**~ 60–65 y**	**~ 10^5 y**	**~ 33–35 y**

(a): In reality the construction phase takes a longer time than 5 years due to public opposition and other sources of delay. Nevertheless, here, those delays are considered to happen in parallel to the R&D and licensing phase, with no impact on the overall time representation.

Table 6.1: Comparison of the reproduction of funds
of nuclear energy vs. fossil energy

After having set the extent (duration) of the analysis, we can now focus on the generation and consumption of the flow elements that are disappearing and/or appearing over the duration of the representation. The grain (time differential) can be evaluated from all unit operations of the process for each one of the two representations. Nevertheless, as discussed earlier, the time differentials corresponding to the operations related to the handling of waste are so long that they can no longer be considered as a flow—their identity changes over a too long time period compared to the overall extent of the system. As a matter of facts, those operations are not considered in the evaluation of the grain of the system which, thus, focuses on the front-end and operation phases (see Table 6.2). That way, no matter which representation we consider for the nuclear energy system, the overall grain—i.e. the time differential between the time when the inflow (natural uranium) enters the system and the time when the corresponding outflows (electricity and waste) exit the system—is equal to about 5–8 years, as shown in Table 6.2.

Now, the comparison of the grain between the two systems shows that nuclear energy is affected by a large inertia. Indeed, when effects of changes in the fuel cycle can be measured after less than one year in the case of fossil energy, these would not be possible to measure before (at least) 5 to 8 years in the case of nuclear energy.

Phase	**Nuclear energy**		**Fossil energy**
	Representation #1 (electricity-oriented)	**Representation #2 (waste-oriented)**	
Mining	< 1 y	< 1 y	< 1 y
Enrichment	~ 1 y	~ 1 y	N/A
Fuel fabrication	~ 1 y	~ 1 y	N/A
Operation	3–5 y	3–5 y	< 1 d
Waste storage	–	*becomes a fund*	N/A
Reprocessing	–	*becomes a fund*	N/A
Waste disposal	–	*becomes a fund*	N/A
Grain	**~ 5–8 y**	**~ 5–8 y**	**< 1 y**

Table 6.2: Comparison of the generation and consumption of flows of nuclear energy vs. fossil energy

The problem of time scale affecting nuclear energy in particular has serious implications on the discussion about alternative energy sources in relation to two crucial points:

(1) the impossibility of making any reliable quantitative assessment in the long term; The comparison presented here demonstrates that any quantitative assessment referring to long term energy scenario involving nuclear energy is meaningless due to the long time durations for each phase of this system. Indeed, in order to make these assessments, it would require to know the technical coefficients, socio-economic institutions and environmental conditions over hundred thousands of years, something which is not possible. Even if looking differently at the speed of the nuclear energy system by ignoring the waste handling phase (representation #1), still, the very low speed at which flows are generated and consumed within that system would require to make assumptions over several decades. Using common sense one should admit that, *by default*, these quantitative assessments are not possible, especially when based on price. Indeed, price—subject to very short term changes—and nuclear energy—affected by a systemic large inertia—are incommensurable. Going further, this discussion makes clear that, instead, energy scenarios should better be based on biophysical analyses that are, *by default*, less subject to changes since they are linked to a certain physical reality—namely an *energetics* reality —while there is no any physical reality behind price-based analyses.

(2) the lack of flexibility and possibility of adaptation to new situations and/or crisis of the nuclear energy system. This problem not only can be deducted from the analysis of the temporal scale of nuclear process but also from direct experience.

The most recent example is probably the still unfolding disaster at the Fukushima-Daiichi nuclear power plant where the accidents happened on old reactors whose design dates from the 1970s corresponding to the early stages of the development of the civilian nuclear industry. This means that those reactors did not fully benefit from the experience of accidents of Three-Mile Island (U.S., 1979) and Chernobyl (ex-USSR, 1986).[11] In fact, this unavoidable inertia affecting the entire nuclear energy system represents one of its major systemic problems in addition to (1) its low economic competitiveness discussed in this study; and (2) the problem of uncertainty affecting safety design (Diaz Maurin, 2011a). The long time scale along with large capital costs involved with nuclear energy investments lead to a lock-in situation in which one technology (thermal neutron reactors) prevails upon other potentially better technologies (e.g. fast neutron reactors) (Cowan, 1990).

6.3 The issue of power level

There is a crucial distinction between *energy* and *power* in energy analysis. Energy (measured in joules or watt-hour electric in our study) can refer to a given amount of a primary energy source (PES) or to a given amount of an energy carrier (EC), but with no reference to time. On the other hand, power (J/s or Wh_{el}/h in our study) indicates the given pace of an energy conversion in time—the rate at which useful work is performed (Giampietro and Mayumi, 2009). This distinction is fundamental to energy analysis because both concepts—energy and power—deal with different types of systemic constraints. Specifically, an assessment of *power level* refers to the expected characteristics of the converter, or—using the terminology proposed by Georgescu-Roegen (1971)—an assessment of power level is required to define the expected characteristics of *fund* elements. In conclusion, information about *power levels* is crucial to detect the viability of a metabolic process in relation to internal constraints (the characteristics of the metabolic system in relation to the *funds*), whereas information about the amount of *energy input* is crucial to detect the viability of a metabolic process in relation to external constraints (the characteristics of the interaction of the metabolic system with its context in terms of *flows*) (Giampietro and Mayumi, 2009). As a matter of facts, any meaningful energy analysis must include both types of information: the consumption of energy input (assessed in Section 4) *and* the power level at which the energy conversion is expected to take place.

This section presents the evaluation of the power level of the nuclear energy and fossil energy systems. To do so, the power level can be assessed only at "local" scale—a country for instance—(Giampietro et al., 2011b). Here, I analyze the exosomatic metabolic pattern of the French society for the year 2008, specifically for the electricity production sector (Figure 6.1). This analysis is derived from Giampietro and Mayumi's (2009) work in which they considered the Italian economy as being a black box and then opened showing its different compartments. In 2008, the population of 62 million French people represented a total of 543.1Gh of *total human activity* (THA). In that same year, the French population consumed 37.273Mtoe (Eurostat, 2008) of commercial electricity or 433.5TWh (1Mtoe ~ 11,630GWh, OECD/IEA, 2005). We

11 Some new safety features can be incorporated during the life of a nuclear reactor, but others cannot. An important characteristics in the design of nuclear reactors is that safety-related assumptions are impacting the rest of the design—being the most *fundamental* assumptions—so that they have to be taken way upstream during the design process.

call this flow of exosomatic electricity the *total exosomatic throughput* (TET_{el})—not to be confused with the TET which is the flow of total exosomatic *energy* (Giampietro and Mayumi, 2009). We can then calculate the *average exosomatic metabolic rate* of the entire society ($EMR_{AS,el}$) as the exosomatic electricity consumption of society per unit of human activity (or *power in consumption*), which equals 800Wh/h (or watts).

We now open the black box (right-hand side of Figure 6.1) and examine the different compartments making up the French economy (left-hand side). We use a multi-level matrix of compartments measured in hours of human activity. In doing so, we discover that out of the 543Gh of total human activity available to French society in 2008, only 44Gh (or 8%) were invested in the production of goods and services (paid work sector or PW), while about 500Gh were allocated to the consumption of goods and services (household sector or HH). Thus, 11 hours of human activity were invested in the consumption for each hour invested in production (500Gh/44Gh).

We now examine the profile of the distribution of work time over the various sub-sectors of the paid work sector, including the energy sector in charge of the mandatory task of supplying exosomatic energy carriers to society. Out of the 44Gh (8% of THA) allocated to the paid work sector, less than 1% was allocated to the energy and water sector. Now, out of this tiny fraction, about 54% were allocated to the electricity production sector. In conclusion, in France in 2008, only a fraction equal to 0.0003 (only 300 millionth) of the total human activity was used for supplying the 433.5TWh of electricity consumed in that year. Thus, dividing the total electricity consumption of France by the hours of work allocated to the energy sector for the production of electricity, we find that the electricity production sector was able to deliver 2.5MWh of exosomatic electricity per hour of work to the society to functions properly ($EMR_{ES,el}$ or *power in supply*). As observed by Giampietro and Mayumi (2009), the energy sector of all developed countries exhibit an extremely high level of power in supply of exosomatic energy, which is also the case for the electricity production sector of countries like France that are exporting electricity.

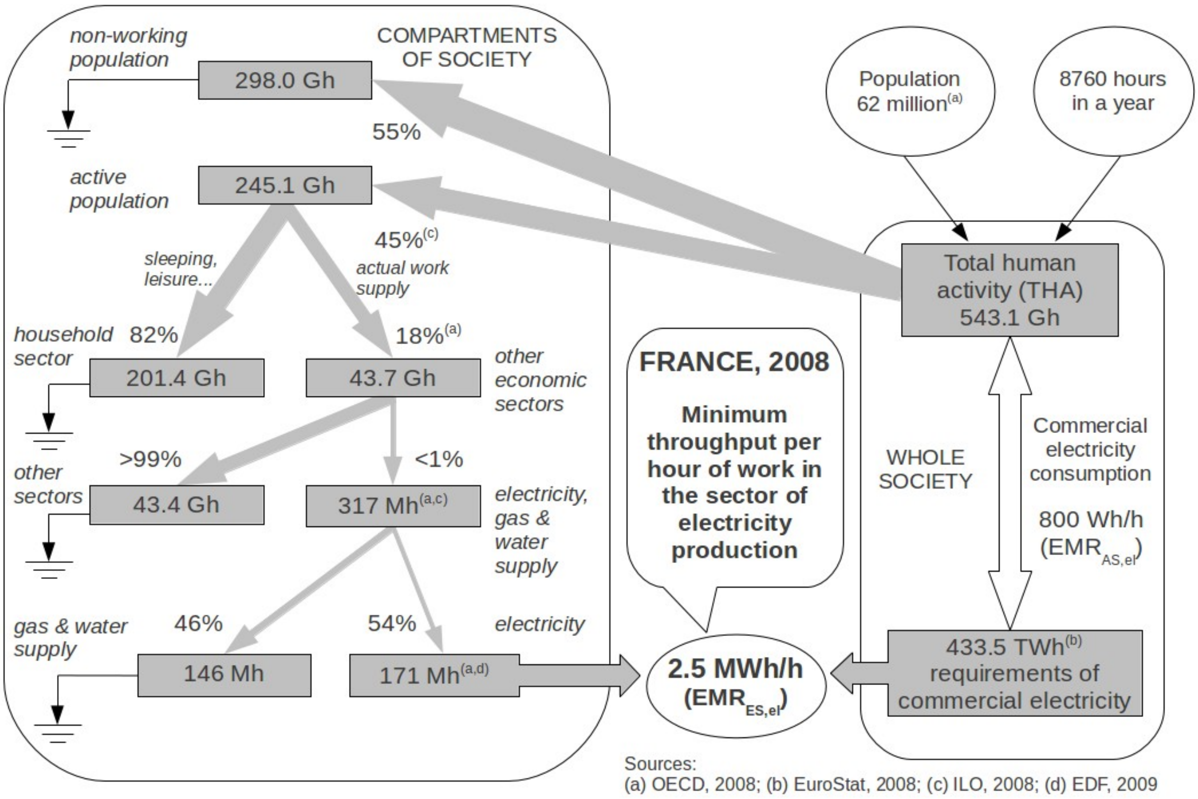

Figure 6.1: Exosomatic electricity flow in French society, 2008

As discussed in Section 2.1.2.2, the formulation of the concept of energy return on investment (EROI) as a simple ratio over two numbers—which does not consider power levels nor the scale of the flows—do not provide a meaningful assessment of a process of exploitation of primary energy sources which requires the consideration of other relevant aspects (Giampietro and Mayumi, 2009; Giampietro et al., 2011b). Here, I propose another analytical tool being the ratio between the power in supply by a specific energy source (e.g. nuclear energy or fossil energy) and the power in supply by the entire energy sector ($EMR_{ES,el}$ evaluated above) corresponding to the minimum throughput of electricity that was needed to meet the *consumption* of commercial electricity of France in 2008. Although such a ratio—namely the *power level ratio*—is not an output/input ratio as the EROI is, it provides information about the power level at which energy carriers have to be invested in the exploitation according to what is required by society, which makes possible to assess the quality of different energy sources.

In the case of France in the year 2008, using the results of the labor requirements found in Section 4, we can compare the level of power in supply of nuclear energy ($EMR_{NE,el}$ in MWh/h) with the one of fossil energy ($EMR_{FE,el}$) in making electricity to the minimum throughput evaluated above ($EMR_{ES,el}$ equal to 2.5MWh/h, as shown in Figure 6.1). In that example, the nuclear energy system presents an $EMR_{NE,el}$ equal to about 1.7MWh/h (570–620h/GWh in Table 4.15) whereas the fossil energy system shows an $EMR_{FE,el}$ equal to 17–20MWh/h (50–60h/GWh in Table 4.15), resulting in a power level ratio equal to about 0.7:1 for nuclear energy and about 7:1 for fossil energy. This result has two implications.

First, as it has already been shown in Section 4.5.4 when evaluating the specific labor requirements, we see that the power level of fossil energy is about 10 times higher than the one of nuclear energy, meaning that, in order to generate the same quantity of net electricity, nuclear energy requires about 10 times more labor efforts (and corresponding indirect energy costs).

Second—and most important implication—when linearizing all costs throughout the life time of the plants, the overall power in supply of the nuclear energy system is inferior to the minimum throughput of electricity required by society in the case of France for the year 2008 (power level ratio inferior to 1:1[12]). This is another serious systemic problem as it demonstrates that nuclear energy cannot guarantee the minimum throughput per hour of work required by society, and is indeed a net *consumer* rather than a net *supplier* in terms of power. In reality, a more refine evaluation would show a power level of the nuclear energy system being even lower since (1) the study does not include all labor requirements of significant phases such as R&D and safety regulation; and (2) the sensitivity analysis shows that labor requirements increase when the quality of ore grade reduces.

The case of France is a useful example for this analysis of power level because in this country nuclear energy largely prevails among other PES in making electricity by representing about 76% of the total production of electricity (CEA, 2009). Nevertheless, we found that this energy source was not able to meet the demand from the society in terms of exosomatic metabolic rate in France in 2008. This means that nuclear energy relied on other PES with much higher power levels—such as fossil energy and hydroelectric power, given the fact that photovoltaics and wind energy were not significant energy sources in France in 2008—to reach the power in supply of electricity required by society from the entire energy sector. And since the French society did not face any significant change in the year 2008 in terms of labor or electricity consumption, the low power level of nuclear energy can be seen as a further systemic problem in the discussion about alternative energy sources.

12 In our formulation of the power level ratio—the power in supply from an energy system over the minimum throughput from the entire energy sector—it is possible to get numbers higher than 1:1—contrary to what should be the proper application of any output/input ratio in net energy analyses—it does not have any energetic meanings but rather assesses the viability of a primary energy source in terms of power level according to what is required by society. Then, a PES can be either a net *supplier* in terms of power level (ratio superior to 1:1) or a net *consumer* (ratio inferior to 1:1).

7. CONCLUSION

7.1 Some inconvenient realities

The biophysical explanation proposed here is based on the use of a grammar capable of analyzing the process of production of electricity in modular elements, defined using semantic and formal categories. In this way it becomes possible to individuate similarities and differences in the process of production of electricity, and then measure and compare “apples” with “apples” and “oranges” with “oranges”.

By adopting this approach, it becomes possible to explain the low economic competitiveness of nuclear energy in the production of electricity. The major systemic problems of economic competitiveness with nuclear energy are found to be related to: (i) its dependence on oil, limiting its possible role as a carbon-free alternative; (iii) the choices made in relation to its fuel cycle, especially whether it includes reprocessing operations or not; (iv) the uncertainty in the definition of the characteristics of its process; (v) its large inertia (lack of flexibility) due to issues of time scale; and (v) its low power level.

As we discussed before, there are several factors making it difficult to define the characteristics of the process of generation of electricity with nuclear energy. First, there is a high variability of the uranium ore grades, and this fact determines large differences in the resulting assessment of the required inputs (costs) in the front-end phases of the process. Second, the time required to establish an operating process of electricity production with nuclear energy is much larger than the one typical of fossil energy powered plants. Moreover, nuclear energy has also a much longer time of immobilization of both the funds (the plant, the facilities for the handling of wastes) and flows (the nuclear fuel and nuclear waste), when compared with fossil energy. This uncertainty in the assessment of the biophysical characteristics of the process translates into a liability for the economic competitiveness of the civil use of nuclear energy for electricity production.

Now, leaving aside the issues of the large level of uncertainty and the severity of the consequences in the case of an accident which are both very relevant for private investors,the biophysical comparison between nuclear energy and fossil energy shows a systemic weakness of nuclear energy as an alternative energy source for the production of electricity. In fact, both indirect fossil-fuel (oil) and labor requirements are higher for nuclear energy than for fossil energy. The fact that nuclear energy for the production of electricity remains dependent on the use of fossil-fuels (another energy carrier) and labor affects it economic competitiveness in comparison with fossil energy.

Therefore, the low competitiveness of nuclear energy has been confirmed to be a systemic problem not due to circumstantial variables. Although there can be certain variations—e.g. further safety measures in the licensing and design of reactors are expected as a response to the recent Fukushima-Daiichi nuclear accidents—this problem can be explained by the very *essence* of the nuclear energy source as explained in the next section.

7.2 The energy intensity dilemma

The problem of the low competitiveness of nuclear energy in comparison with fossil energy in making electricity can be seen first and foremost as a (systemic) problem of scale—both in space and time. By adopting this narrative the lack of competitiveness of nuclear energy can be explained looking at the very essence of this primary energy source, i.e. the scale of its *energy intensity*.

According to Polimeni and Mayumi (2011), "*fossil fuels are 'optimal' in terms of the amount of matter in bulk required for energy extraction, transformation, and transportation to support modern industrial society*". This superiority of fossil energy over nuclear energy in making electricity has also been observed using the quantitative analysis proposed in this study. But in more general terms, fossil fuels have demonstrated their superiority over other primary energy sources since their massive use led to time and land savings in the energy and agricultural sectors which have been then reallocated to various sectors of the modern economy, resulting in changes in the metabolic pattern of society (Giampietro et al., 2011a). No other primary energy source can claim such a superiority in terms of material flow requirements, explanation often called "Georgescu-Roegen's Fundamental Proposition" (Kawamiya, 1983, in: Polimeni and Mayumi, 2011).

According to Georgescu-Roegen, the high quality of fossil energy—being related the material flows—can also be associated with the scale of energy intensity (Georgescu-Roegen quoted in: Mayumi and Polimeni, 2011): "*It [the necessary amount of matter for a technology] is high for weak-intensity energy (as is the solar radiation at the ground level) because such energy must be concentrated into a much higher intensity if it is to support the intensive industrial processes as those now supported by fossil fuels*". Georgescu-Roegen also argues that the necessary amount of matter is high for high-intensity energy—such as thermonuclear energy—because high-intensity energy must be contained and controlled within a stable boundary. This issue can be called the *energy intensity dilemma* or *Kawamiya's dilemma* from the name of the person who first explained the high quality of fossil energy through its optimal energy intensity (Kawamiya, 1983 in: Giampietro et al., 2011b).

The energy intensity dilemma can be explained as follows. In the case of fossil fuels, a set of physical transformations carried out in the exploitation of a PES are referring to energy forms defined on the similar space-time scale at which endosomatic conversions[13] are used to operate (Giampietro et al., 2011b). On the contrary, the high density of the process of nuclear energy is so high that it requires large investments in diluting, slowing down and containing the set of energy transformations. This entails a discrepancy of scale between the very high density of the process of production and the relative low density of the process of utilization of energy (the Rankine cycle generating electricity in the power plant) resulting in huge stocks of radioactive material (beside the waste heat) that have to be accumulated *after* the utilization of energy takes place. On the other hand of this dilemma, the solar radiation reaches the Earth in a so diluted form that it requires large investments in power capacity, for collecting and transforming it in a more concentrated form. This also entails a discrepancy of scale between the low density of the process of production and the high density of the process of utilization requiring huge stocks of chemical energy to be accumulated *before* the utilization of energy takes place (Giampietro et al., 2011b). This is illustrated in Figure 7.1.

13 Physiological conversions of different types of energy inputs – i.e. food items – into end-uses that take place inside the human body . (Giampietro and Mayumi, 2009)

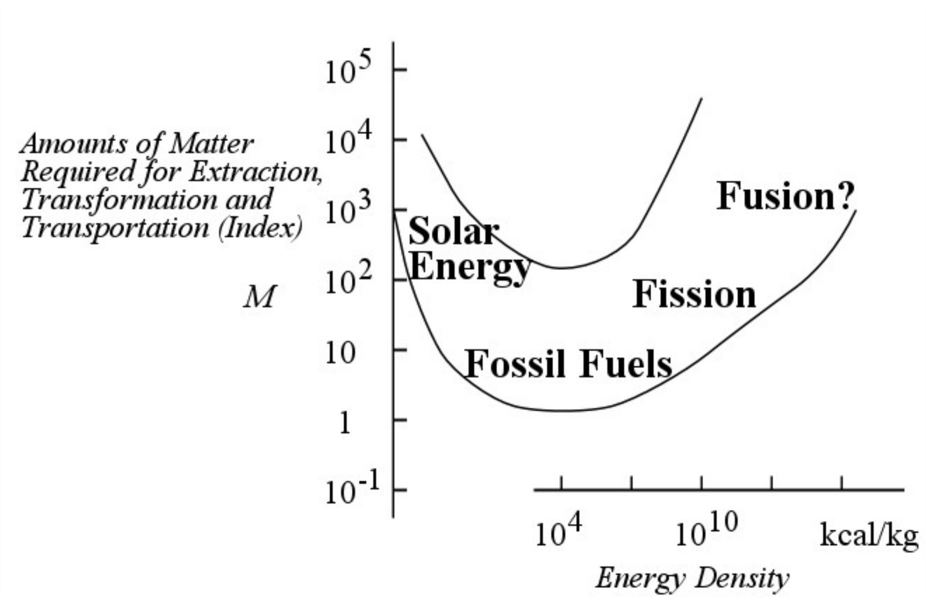

Figure 7.1: Amounts of material requirement and energy density for different PES (Source: after Kawamiya, 1983 in: Giampietro et al., 2011b)

In summary, the extreme density of nuclear energy requires a too large investment in the various steps of the process to dilute the energy flows to a level that can be handled by conventional technologies (the Rankine cycles used to transform thermal energy into mechanical energy). In a way, we can see in the too high density of nuclear energy the opposite problem found with direct solar radiation, too diluted and requiring large investments to be concentrated into usable forms. The fundamental consequence of this energy intensity dilemma is that neither solar energy nor nuclear energy can maintain the current metabolic pattern of modern society based on the massive use of fossil fuels as primary energy sources.

REFERENCES

Ahmadi, P., Dincer, I. and Rosen, M.A. (2011, *in press*) *Exergy, exergoeconomic and environmental analysis and multi-objective optimization of a CCPP with supplementary firing using an evolutionary algorithm*, Energy

ANDRA (2008) *Rapport d'activité*, Agence Nationale pour la Gestion des Déchets Radioactifs. URL:http://www.andra.fr/download/site-principal/document/editions/24ra_2008.pdf

Arthur, B. (1989) *Competing Technologies, Increasing Returns, and Lock-In by Historical Events*, The Economic Journal 99(394):116–131. URL:http://www.jstor.org/stable/2234208

Ayres, R.U., Ayres, L.W. and Warr, B. (2003) *Exergy, power and work in the US economy, 1900–1998*, Energy 28(3):219–273. doi:10.1016/S0360-5442(02)00089-0

Bardi, U. (2009) *Peak oil: The four stages of a new idea*, Energy 34:323–326. doi:10.1016/j.energy.2008.08.015

BBC (2011) *Tepco confirms extra partial fuel rod meltdown at plant*, BBC News, UK (24 May 2011). URL:http://www.bbc.co.uk/news/business-13497656

Bidwai, P. (2011) *People vs Nuclear Power in Jaitapur, Maharashtra* , Economic & Political Weekly (Mumbai) 46(8):10–14. URL:http://epw.in/epw/uploads/articles/15728.pdf

Bodansky, D. (2004) *Nuclear energy: principles, practices, and prospects*, Springer, New York, 2nd ed.

Bradford, P. (2010) *Honey I Shrunk the Renaissance: Nuclear Revival, Climate Change, and Reality*, Electricity Policy. URL:http://www.electricitypolicy.com/index.php?option=com_content&view=article&id=2553:honey-i-shrunk-&catid=99:article&Itemid=710

Brown, M.T. (2004) *A picture is worth a thousand words: energy systems language and simulation*, Ecological Modelling 178:83–100. doi:10.1016/j.ecolmodel.2003.12.008

Bupp, I.C. and Derian, J.C. (1978) *Light Water: How the Nuclear Dream Dissolved*, Basic Books, New York

CEA (2010) *Nuclear power plants in the world (Ed. 2010)*, Commissariat à l'Énergie Atomique, ISSN 1280-9039. URL:http://www.cea.fr/content/download/49912/925958/file/Elecnuc2010_les_centrales_nucleaires_dans_le_monde.pdf

CEA (2009) *Nuclear power plants in the world (Ed. 2009)*, Commissariat à l'Énergie Atomique, ISSN 1280-9039. URL:http://www.cea.fr/content/download/23529/379594/file/Elecnuc2009_les_centrales_nucleaires_dans_le_monde.pdf

Cleveland, C.J. (2005) *Net energy from oil and gas extraction in the United States, 1954–1997*. Energy 30:769–782. doi:10.1016/j.energy.2004.05.023

Cleveland, C.J., Costanza, R., Hall, C.A.S. and Kaufmann, R. (1984) *Energy and the U.S. Economy: A Biophysical Perspective*, Science 225:890–897. doi:10.1126/science.225.4665.890

Cleveland, C.J., Kaufmann, R. and Stern, S.I. (2000) *Aggregation and the role of energy in the economy*, Ecological Economics 32(2):301–317. doi:10.1016/S0921-8009(99)00113-5

Coderch Collell, M. (2009) *El interrogante nuclear: situación, perspectivas e incertidumbres del anunciado 'renacimiento nuclear' (DT 32/2009)*, Real Instituto Elcano, Madrid, Spain. URL:http://www.realinstitutoelcano.org/wps/portal/rielcano/contenido?WCM_GLOBAL_CONTEXT=/elcano/elcano_es/zonas_es/dt32-2009

Cowan, R. (1990) *Nuclear Power Reactors: A Study in Technological Lock-in*, The Journal of Economic History 50(3):541–567. URL:http://www.jstor.org/stable/2122817

Darmstadter, J. (1999) *Innovation and Productivity in U.S. Coal Mining*, in R.D. Simpson (Ed.) *Productivity in natural resource industries: improvement through innovation*, RFF Press, Earthscan. ISBN:978-0915707997

Diaz Maurin, F. (2011a) *Fukushima: Consequences of Systemic Problems in Nuclear Plant Design*, Economic & Political Weekly (Mumbai) 46(13):10–12. URL:http://epw.in/epw/uploads/articles/15865.pdf

Diaz Maurin, F. (2011b) *The nuclear industry is not like the car industry!, In: Our Energy Futures*, Institute of Environmental Science and Technology, Universitat Autònoma de Barcelona, Spain. URL:http://ourenergyfutures.org/actualite-nid-3.html

Deutch, J., Forsberg, C.W., Kadak, A.C., Kazimi, M.S., Moniz, E.J., Parsons, J.E., Yangbo, D. and 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/

Deutch, J. (Co-Chair), Moniz, E.J. (Co-Chair), Ansolabehere, S., Beer, J., Ellerman, A.D., Friedmann, S.J., Herzog, H., Jacoby, H.D., Joskow, P.L., McRae, G., Lester, R. and Steinfeld, E. (2007) *The Future of Coal: An Interdisciplinary MIT Study*, Cambridge, Mass.: Report for Massachusetts Institute of Technology, ISBN:978-0-615-14092-6. URL:http://web.mit.edu/coal/

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. and Todreas, N.E. (2003) *The Future of Nuclear Power: An Interdisciplinary MIT Study*, Cambridge, Mass.: Report for Massachusetts Institute of Technology, ISBN:0-615-12420-8. URL:http://web.mit.edu/nuclearpower/

Dittmar, M. (2011a, *in press*) *Nuclear energy: Status and future limitations*, Energy. doi:10.1016/j.energy.2011.05.040

Dittmar, M. (2011b) *The End of Cheap Uranium*, arXiv:1106.3617v2 [physics.soc-ph]

Eurostat (2008) *Final energy consumption of electricity (ten00097)*, Eurostat, European Commission. URL:http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/main_tables

Fairley, P. (2011) *A Worldwide Nuclear Slowdown Continues*, Technology Review, Massachusetts Institute of Technology (May 18, 2011). URL:http://www.technologyreview.com/energy/37595/

Funtowicz, S. O. and Ravetz, J. R. (1990) *Post normal science: a new science for new times*, Scientific European 266:20–22

Gaudreau, K., Fraser, R.A. and Murphy, S. (2009) *The Tenuous Use of Exergy as a Measure of Resource Value or Waste Impact*, Sustainability 1:1444–1463. doi:10.3390/su1041444

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

Giampietro, M. and Mayumi, K. (2009) *The Biofuel Delusion: The Fallacy of Large-scale Agro-biofuel Production*, London: Earthscan

Giampietro, M. and Sorman, A.H. (2011, *forthcoming*) *Are energy statistics useful for making energy scenarios?*, Energy

Giampietro, M., Mayumi, K. and Munda, G. (2006) *Integrated assessment and energy analysis: Quality assurance in multi-criteria analysis of sustainability*, Energy 31(1):59–86. doi:10.1016/j.energy.2005.03.005

Giampietro, M., Mayumi, K. and Sorman, A.H. (2011a, *in press*) *The metabolic pattern of societies: where economists fall short*, Routledge, Taylor & Francis Group, London

Giampietro, M., Mayumi, K. and Sorman, A.H. (2011b, *in press*) *The Energetics of Modern Societies: cutting throughout the confusion*, Springer

Grubler, A. (2010) *The costs of the French nuclear scale-up: A case of negative learning by doing,* Energy Policy 38(9):5174–5188. doi:10.1016/j.enpol.2010.05.003

Hall, C.A.S. (2008a) *The Energy Return of Nuclear Power*, EROI on the web: (Part 4 of 6), The Oil Drum. URL:http://www.theoildrum.com/node/3877

Hall, C.A.S. (2008b) *Why EROI matters*, EROI on the web: (Part 1 of 6), The Oil Drum. URL:http://www.theoildrum.com/node/3786

Hall, C.A.S., Cleveland, C.J. and Kaufman, R. (1986) *Energy and Resource Quality*, John Wiley & Sons, New York

Hannon, B. (1982) *Energy discounting*, Technological Forecasting and Social Change 21(4):281–300. doi:10.1016/0040-1625(82)90042-7

Hirsch, R.L., Bezdek, R. and Wendling, R. (2005) *Peaking of world oil production: impacts, mitigation, & risk management*, AIChE 52(1):2–8. doi:10.1002/aic.10747

Hore-Lacy, I. (2004) *Uranium Mining, Processing, and Enrichment*, in Cleveland, C.J. (Ed.), 2004, Encyclopedia of Energy, Vol.6, pp. 317–328, Elsevier, Boston

IAEA (2009) *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030*, International Atomic Energy Agency, Vienna, ISBN:978-92-0-109809-2. URL:http://www-pub.iaea.org/MTCD/publications/PDF/RDS1-29_web.pdf

ITER Organization (2011) *ITER & Beyond*. URL:http://www.iter.org/proj/iterandbeyond

Katzer, J. (Dir.), Deutch, J. (Co-Chair), Moniz, E.J. (Co-Chair), Ansolabehere, S., Beer, J., Ellerman, A.D., Friedmann, J., Herzog, H., Jacoby, H.D., Joskow, P.L., McRae, G., Lester, R. and Steinfield, E. (2007) *The Future of Coal: Options for a Carbon-Constrained World*, Cambridge, Mass.: Report for Massachusetts Institute of Technology, ISBN:978-0-615-14092-6. URL:http://web.mit.edu/coal/

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. (2011) *The Future of the Nuclear Fuel Cycle: An Interdisciplinary MIT Study*, Cambridge, Mass.: Report for Massachusetts Institute of Technology, ISBN:978-0-9828008-4-3. URL:http://web.mit.edu/mitei/research/studies/nuclear-fuel-cycle.shtml

Kerr, R.A. (2011) *Peak Oil Production May Already Be Here*, Science 331:1510–1511. doi:10.1126/science.331.6024.1510

Koornneef, J., van Keulen, T., Faaij, A. and Turkenburg, W. (2008) *Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO2*, International Journal of Greenhouse Gas Control 2(4):448–467. doi:10.1016/j.ijggc.2008.06.008

Kopits, S. (2011) *Energy Brief - Oil, the Economy and Policy,* Presentation to the US House of Representatives Energy Subcommittee in Washington D.C., Douglas-Westwood. URL:www.dw-1.com/files/category.php?catID=14

Lenzen, M. (2008) *Life cycle energy and greenhouse gas emissions of nuclear energy: a review*, Energy Conversion Management, 49:2178–2199. doi:10.1016/j.enconman.2008.01.033

Mayumi, K. and Polimeni, J.M. (2011, *forthcoming*) *Uranium Reserve, Nuclear Fuel Cycle Delusion, CO2 Emission from the Sea, and Electricity Supply: Reflections after the Fuel Meltdown of Fukushima Nuclear Power Units*, Ecological Economics

Murphy, D.J. and Hall, C.A.S. (2010) *Year in review–EROI or energy return on (energy) invested*, Annals of the New York Academy of Sciences, Issue: Ecological Economics Review 1185:102–118. doi:10.1111/j.1749-6632.2009.05282.x

NEI (2010) *Blue Ribbon Commission on America's Nuclear Future, Subcommittee on Reactor and Fuel Cycle Technology: Testimony for the Record*, Nuclear Energy Institute, Department for the Industry Infrastructure and Supply Chain, Washington, DC, August 31, 2010. URL:http://www.nei.org/publicpolicy/congressionaltestimony/august-31-2010/

NRC (2011a) *Uranium Mill Tailings*, U.S. Nuclear Regulatory Commission. URL:http://www.nrc.gov/waste/mill-tailings.html (last updated March 12, 2011)

NRC (2011b) *Deconversion of Depleted Uranium*, U.S. Nuclear Regulatory Commission URL:http://www.nrc.gov/materials/fuel-cycle-fac/ur-deconversion.html (last updated March 31, 2011)

NRC (2011c) *Low-Level Waste*, U.S. Nuclear Regulatory Commission. URL:http://www.nrc.gov/waste/low-level-waste.html (last updated April 27, 2011)

Odum, H. T. (1996) *Environmental Accounting: Emergy and Environmental Decision Making*, John Wiley, New York, NY

Odum, H.T. (1971) *Environment, Power and Society*, Wiley-Interscience, New York, NY, 336pp.

OECD (2008) *Average annual hours actually worked per worker*, Summary tables, Annual labour force statistics. URL:http://stats.oecd.org/Index.aspx?DataSetCode=ANHRS

OECD/IAEA (2010) *Nuclear Technology Review*, International Atomic Energy Agency. URL:http://www-pub.iaea.org/MTCD/publications/PDF/NTR2010_web.pdf

OECD/IAEA (2004) *Uranium 2003: Resources, Production and Demand*, International Atomic Energy Agency, ISBN:92-64-01673-2. doi:10.1787/uranium-2003-en

OECD/IEA (2005) *Energy Statistics Manual*, Eurostat, International Energy Agency. URL:http://www.iea.org/stats/docs/statistics_manual.pdf

Pearce, J.M. (2008) *Thermodynamic limitations to nuclear energy deployment as a greenhouse gas mitigation technology*, International Journal of Nuclear Governance, Economy and Ecology 2(1):113–130. doi:10.1016/S0920-3796(00)00158-7

Rothwell, G. (2009) *Market Power in Uranium Enrichment*, Science & Global Security 17:132–154. doi:10.1080/08929880903423586

Rothwell, G. (2010) *International light water nuclear fuel fabrication supply: Are fabrication services assured?*, Energy Economics 32:538–544. doi:10.1016/j.eneco.2009.08.012

Rubin, E.S., Chen, C. and Rao, A.B. (2007) *Cost and performance of fossil fuel power plants with CO2 capture and storage*, Energy Policy 35(9):4444–4454. doi:10.1016/j.enpol.2007.03.009

Schneider, M. and Marignac, Y. (2008) *Spent Nuclear Fuel Reprocessing in France*, Research Report No. 4, International Panel on Fissile Materials (April 2008). URL:www.fissilematerials.org/ipfm/site_down/rr04.pdf

Sciubba, E. (2010) *On the Second-Law inconsistency of Emergy Analysis*, Energy 35(9):3696–3706. doi:10.1016/j.energy.2010.05.015

Smil, V. (2008) *Energy in Nature and Society: General Energetics of Complex Systems*, MIT Press, Cambridge, MA

Spath, P.L., Mann, M.K. and Kerr, D.R. (1999) *Life Cycle Assessment of Coal-fired Power Production*, National Renewable Energy Lab., U.S. Department of Energy. doi:10.2172/12100

U.S. Congress (2005) *Energy Policy Act of 2005 (Public Law 109-58, Aug. 8, 2005, 119 Stat. 594)*, U.S. Congress. URL:http://www.gpo.gov/fdsys/pkg/PLAW-109publ58

U.S. EIA (2008a) *Table 18. Average Number of Employees by State and Mine Type*, Energy Information Administration. URL:http://www.eia.doe.gov/cneaf/coal/page/acr/table18.html

U.S. EIA (2008b) *Table 1. Coal Production and Number of Mines by State and Mine Type*, Energy Information Administration. URL:http://www.eia.doe.gov/cneaf/coal/page/acr/table1.html

U.S. EIA (2010) *International Energy Outlook 2010, DOE/EIA-0484(2010),* U.S. Department of Energy, Energy Information Administration. URL:www.eia.gov/oiaf/ieo/index.html

U.S. EPA (2006) *Technologically Enhanced Naturally Occurring Radioactive Materials From Uranium Mining, Volume 1: Mining and Reclamation Background*, U.S. Environmental Protection Agency, EPA 402-R-05-007 (updated June 2007). URL:http://www.epa.gov/rpdweb00/docs/tenorm/402-r-08-005-voli/402-r-08-005-v1.pdf (retrieved on April 7, 2011)

U.S. Department of Labor (2007) *NAICS 221100 - Electric Power Generation, Transmission and Distribution*, Bureau of Labor Statistics, U.S. Department of Labor. URL:http://www.bls.gov/OES/current/naics4_221100.htm

U.S. Department of State (2010) *New START Treaty,Treaty between the United States of America and the Russian Federation on Measures for the Further Reduction and Limitation of Strategic Offensive Arms*, U.S. Department of State, Apr 8, 2010. URL:http://www.state.gov/documents/organization/140035.pdf

WCI (2009) *The Coal Resource: A Comprehensive Overview of Coal, Section 2: Coal Mining*, World Coal Institute. URL:http://www.worldcoal.org/bin/pdf/original_pdf_file/underground_and_surface_mining(01_06_2009).pdf

WISE (2009a) *Nuclear Fuel Material Balance Calculator*, World Information Service on Energy, Uranium Project, Arnsdorf, Germany. URL:http://www.wise-uranium.org/nfcm.html (last updated 23 Nov 2009)

WISE (2009b) *Recycled Nuclear Fuel Cost Calculator*, World Information Service on Energy, Uranium Project, Arnsdorf, Germany. URL:http://www.wise-uranium.org/nfccr.html (last updated 12 Nov 2009)

Yang, C.J. (2009) *Belief-based energy technology development in the United States: a comparison of nuclear power and synthetic fuel policies*, Cambria Press, Amherst, NY