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HOW SERIOUS IS THE ADDICTION TO OIL OF DEVELOPED SOCIETY? A MULTI-SCALE INTEGRATED ANALYSIS BASED ON THE CONCEPT OF SOCIETAL AND ECOSYSTEM METABOLISM: PART 2

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Abstract

In these years the growing concern for both global warming and peak oil has put the energy issue back on the front burner of the political debate. In technical terms, this implies looking for alternatives to fossil energy as the primary energy source powering the economic process of modern economies. This paper (the second of series of two) presents a methodological approach called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism, which can be used to study this problem. After a short introduction, section one presents the basic rationale and the theoretical building blocks of this approach (*Mosaic Effect Across Levels* and *Impredicative Loop Analysis*). Section two presents a few results of previous applications of this method which confirm its validity, then illustrates how MSIASEM can be used for checking the feasibility and desirability of alternative energy sources. Finally, the last section of this paper illustrates the link between societal and ecosystem metabolism, which makes it possible to study the compatibility of societal metabolism on its interface with ecological processes. In conclusion, with this paper we claim that the MSIASEM approach can provide a heuristic vision of the "quality" of potential alternatives to fossil energy, due to its ability to contextualize such an analysis in relation to the characteristics of the metabolism of a given society, the characteristics of its energy sector and the characteristics of the metabolism of the ecosystems embedding them.

Keywords

Multi-scale analysis, Integrated Analysis, Societal Metabolism, Bio-economics, Energy Analysis, EROI, peak oil, fossil energy, alternative energy sources

1. Introduction

In this paper we present an analytical method which backs-up the validity of the two metaphors used in the first paper of this series, when discussing the desirability and viability of biofuels as an alternative to fossil energy. The analytical approach is called Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MSIASEM). It provides a flexible system of accounting useful for developing a quantitative analysis based on these metaphors. The peculiarity of this approach is that it makes it possible to handle the epistemological challenge entailed by the special nature of the metabolism of dissipative systems, which is organized on multiple-scales. As a matter of fact, to avoid dangerous blunders, when dealing with metabolic systems operating simultaneously on different scales, it is important to address explicitly the scientific challenges associated with this fact. The text is organized in three parts: Part 1 provides a general presentation of the basic rationale of this methodology and introduces its theoretical building blocks (Mosaic Effect Across Levels and Impredicative Loop Analysis); Part 2 provides an overview of results of previous applications supporting the claim that this approach is useful for: (i) the study of changes in the patterns of exosomatic metabolism of socio-economic systems; (ii) a comparison of different countries; (iii) a quality check on the credibility of scenarios; and (iv) an integrated analysis of the quality of energy sources. According to the material presented in this section it is easy to see that current addiction to oil of modern societies is a serious problem. Finally, Part 3 illustrates the natural link between a multi-scale analysis of societal metabolism and a multi-scale analysis of ecosystem metabolism. This makes it possible to interface a bio-economics analysis of socio-economic systems to ecological analyses to study their environmental impact.

2. Multi-scale integrated analysis of societal and ecosystem metabolism: basic theory and building blocks

2.1.1 Acknowledging the epistemological challenge associated with multiple scales: neglecting the relevance of multiple-scales can generate blunders

Consider the following example: The myth of excess energy-food intake in the diet of the rich versus the energy-food shortage in the diet of the poor. This example deals with the conventional narrative used to characterize the *endosomatic* metabolism of developed countries versus that of developing countries. The standard approach used in the international debate has been adopted in the following two quotes (Alexandratos, 1999)*:* (i) "the part of world population living in countries where per person food supplies *are still very low - under 2,200 kcal/day*"; (ii) "*the very high levels* of food availability generally found in the statistics of many high-income countries, often *over 3,500 kcal/person/day*." This narrative, which has been used for decades to deal with the issue of malnutrition and inequity at the global level, is based on the choice of two benchmark values: (a) 2,200 kcal/day per person; associated with a very low level of food energy intake; and (b) 3,500 kcal/day per person; associated with a very high level of food energy intake.

We happen to believe that these benchmarks are not particularly useful for several reasons. First, if the goal is to characterize the energy intake of a population (something defined at the hierarchical level *n*), it is not wise to use a variable referring to the level of consumption per day of an individual person (at a different and lower hierarchical level of analysis). Second, a robust characterization of the metabolism of a population requires more data sources (number of external referents for generating the relative data set) than just a simple ratio among two numbers (total food intake of a population and population size).

An alternative method to assess *endosomatic metabolism* (food consumption) of these societies, which explicitly addresses the existence of different hierarchical levels of analysis (population level *versus* individual level) can be obtained looking at this consumption in terms of metabolic flows. In this way, the energy intake is mapped against the human mass which is metabolizing it, after addressing the specific characteristics of the "human mass." This approach is shown in the two characterizations of the metabolic rate of food energy consumption per capita of a developed and a developing country in Fig. 1. The two graphs (1a and 1b) show the representation of a kg of body mass as a fund variable used to describe the metabolism of food in human society.

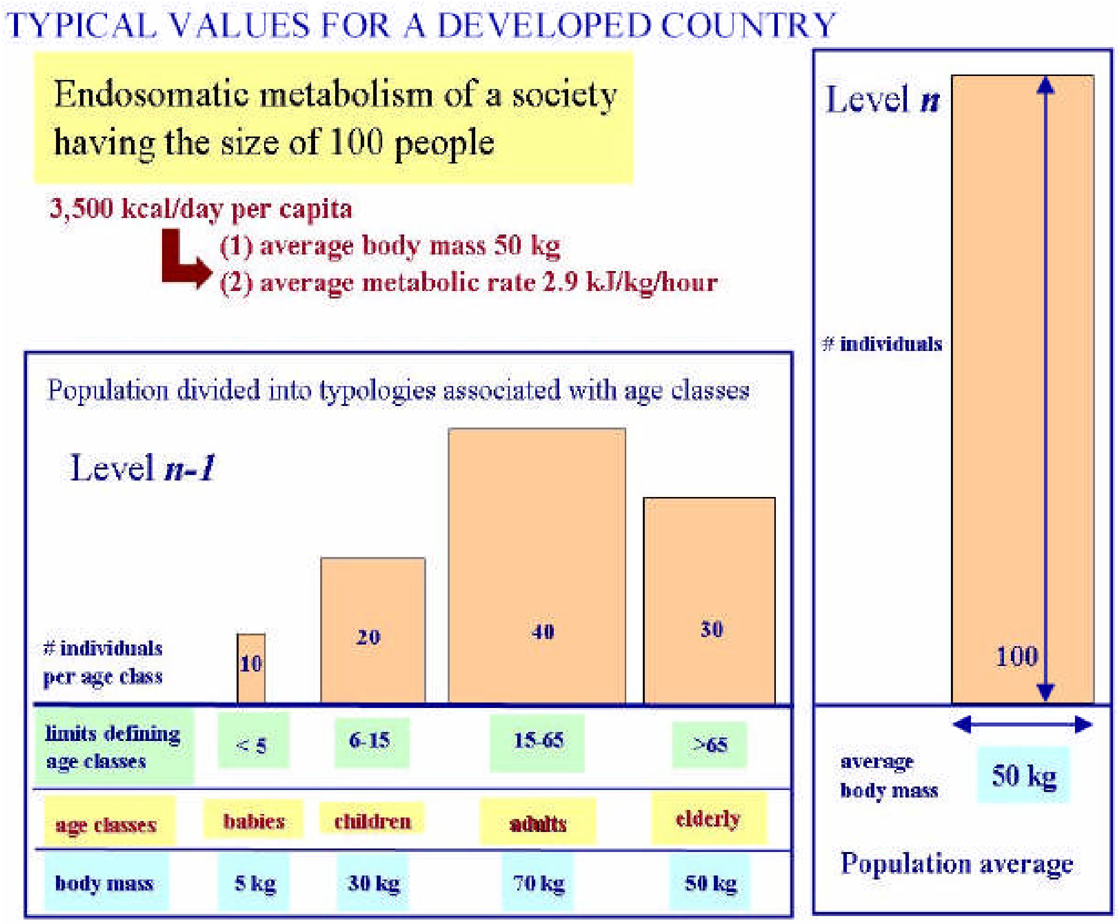


Figure 1a. Typical values of endosomatic metabolism for developed countries.

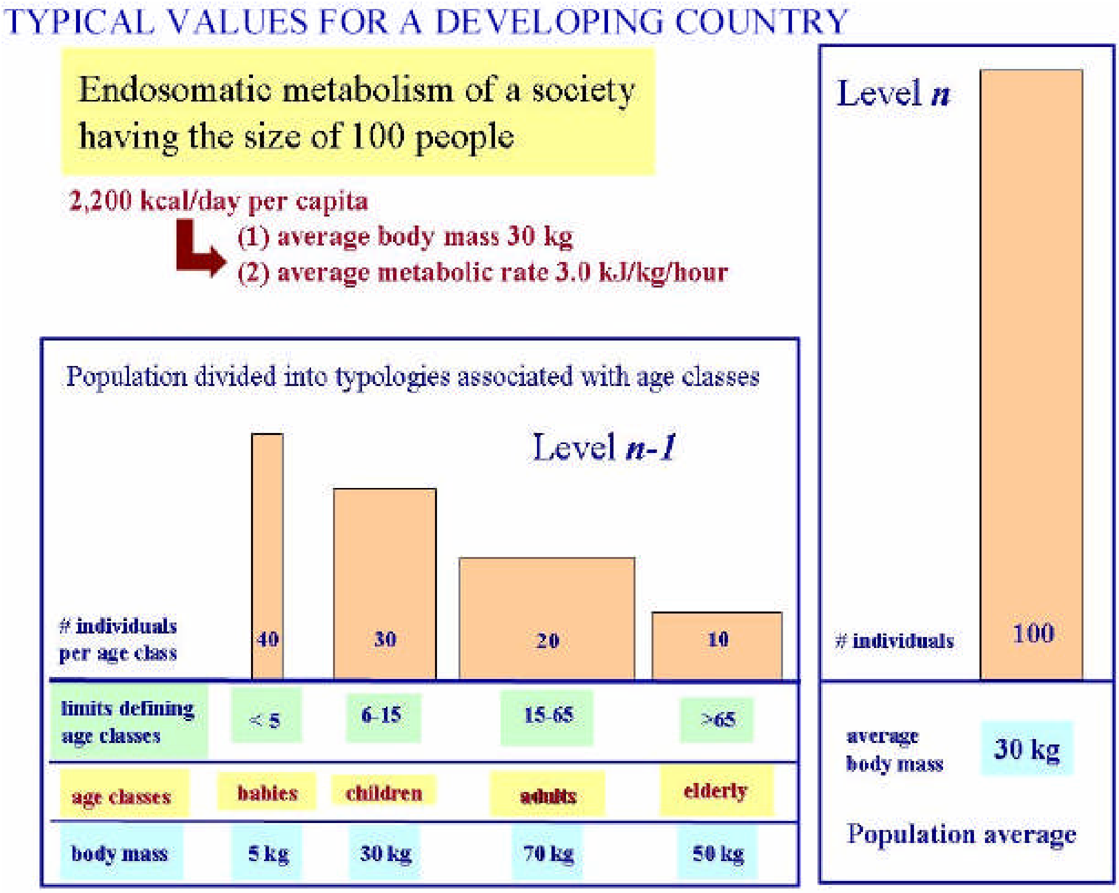


Figure 2b. Typical values of endosomatic metabolism for developing countries.

Using the terminology introduced by Georegescu-Roegen (1974) for the analysis of dissipative systems, it is possible to make a distinction between: (i) *fund variable*, which is referring to an observable quality which is present before, during and at the end of the analysis (in this example, kg of human mass); and (ii) *flow variable*, which is referring to an observable quality that is dissipated during the period of observation and therefore disappear at the end of it (in this example, the kcalories of food that are metabolized by the human mass). Another characteristic of fund coordinates is that the characteristics of the observable quality (e.g. human mass) do affect the intensity of the flow variable (e.g. food energy consumed per day per kg of human mass). In relation to the fund variable "kg of human mass" there are two non-equivalent ways for assessing the total amount of human mass of a population.

#1 characterizing the population at the level of the whole society – in this case after determining the average body mass of the population (e.g. 50 kg per individual in a developed country), we can multiply this value for the number of people (e.g. 100), to obtain a total human mass of 5,000 kg for 100 people of a developed country.

#2 characterizing the population of the whole society as determined by a combination of the characteristics of lower level compartments. In this case, we

have to select a set of significant components of the population that can be associated with expected typologies (e.g. different age classes for which we can estimate the expected weight of individual instances). An assessment of the value for the whole population can be obtained by using the profile of distribution of the individuals over the selected set of relevant typologies.

The two approaches are represented in Fig. 1a (for developed countries) and Fig. 1b (for developing countries): (i) on the right a single assessment of the overall weight as a combination of weight per individual (width of the bar) and number of individuals (height of the bar), and (ii) on the left an assessment based on a combination of the expected weight of individuals belonging to each one of the age classes considered (babies, children, adults, elderly) – the width of each of the bars associated with each age class - and the profile of the distribution of the population over the given set of age classes - the height of each of the bars associated with the number of individuals in each age class.

The differentiation in two methods of characterization did not provide any real mosaic effect, since the two data sets required for these two characterizations (on the left and on the right) are the same. That is, you must know the profile of distribution of individuals over the selected set of age classes and the average weight of individuals belonging to the various age classes (data for characterization using the method #2) in order to be able to calculate an average body mass at the level of the population (data for characterization using the method #1). However, things change when considering the metabolic rate of the same system across these two different levels (assuming the whole population as level *n*; and the individual age class as level *n-1*). In fact, the rate of food energy consumption of a given population can be assessed using:

method #1 - by dividing the total food consumption by the population size (using national statistics) by the number of individuals; and

method #2 - by expressing the metabolism of the total mass of human population as a combination of different typologies of metabolic rates of energy consumption per kg of body mass associated to different age classes. With this approach, we can express the total consumption of food energy of a population using three variables:

(1) Total Food Energy: a flow-type variable we want to measure (kcal/day);

(2) Total Human Mass: a fund-type variable associated with characteristics that will affect the pace of the flow variable (kg);

(3) Average Metabolic Flow: the ratio between the flow-type and the fund-type variable (kcal/kg/day).

This third variable has a peculiar characteristic. The value of this intensive variable can be associated to different typologies of metabolic systems across different levels independently from the size of the metabolic system. That is, it is possible to study, using different data sources, the "typical" Average Metabolic Flow (kcal/kg/day) of a given population, a given household, an age class, a person, the whole humankind.

The combined use of fund-type variables, flow-type variables and their ratio introduces the possibility of using non-equivalent sets of external *referents* (data source) for the assessment of energy consumption of a society. In fact, knowledge about the metabolism of human body mass belonging to different age classes (e.g. "individuals between 3 and 5," or "individuals over 85") and referring to different typologies of human populations (e.g. populations of different countries found in the world) can be obtained from physiological and nutritional studies (e.g. an example of a data set like this organized in excel data spreadsheet is available in James and Schofield, 1990). In this case, this implies that the total amount of energy consumed by a population can be estimated in parallel using two distinct methods and two distinct data sets: (i) at the national level, by dividing the total consumption of food per year, by the size of population; (ii) on the interface of two levels of aggregation: the age class level (level *n-1*) and the national level (level *n*), by combining the knowledge of the expected metabolism of each age class and the profile of distribution of individuals over age classes.

The possibility of using two non-equivalent external sources of data in parallel is called *Mosaic Effect Across Levels* (for more see Giampietro and Mayumi, 2003a). This is an analysis which is peculiar for metabolic systems. In fact, metabolic systems are capable of expressing a predictable behavior - by defining for themselves what is metabolized and at what pace - in parallel on different levels. That is, when dealing with human beings (at the level of individual human beings) it is possible to guess: (i) a set of benchmark values characterizing such a metabolism; and (ii) that the metabolism of any individual human being is the result of the metabolism of its components (when analyzing the metabolism at the level of organs). In the same way, the metabolism of a household is the result of the metabolism of its lower level individual elements. By assessing the characteristics of the metabolism of different nested elements, studied in parallel across levels, it becomes possible to obtain a *Mosaic Effect*.

Keeping in mind this multi-level analysis it is possible to evaluate the usefulness of the two benchmarks adopted in the conventional narrative about nutrition in developed and developing countries (entailing that the value of 2,200 kcal/day per capita indicates a shortage of food-energy input). Looking at Fig. 1, we can note that the difference between 2,200 kcal/day and 3,500 kcal/day when such an assessment is expressed in Joules of food energy per kg of body mass per hour simply does not exist. Actually, people living in developing countries – characterized using the benchmark of 2,200 kcal/day - are metabolizing per kg of body mass and per hour *more* food energy than people living in developed countries! The difference in the benchmark proposed by the conventional narrative (3,500 versus 2,200) has nothing to do with the pace of food energy metabolized within human bodies, but simply reflects a difference in the value of the average body mass per capita of the population (50 kg is the average per person in developed countries, versus 30 kg of average per person in developing countries). This difference is related mainly to a difference in the profile of distribution of the population over age classes, which, in turn, is explained by a difference in life span (for a more detailed discussion of this point see Giampietro et al. 1993).

Obviously, there is a difference in the nutritional status of people living in developed and developing countries as shown by the difference in life span. Actually, the multi-level analysis based on: (i) differences in the profile of distribution of individuals over age-classes; and (ii) the definition of the relative set of metabolic rates, clearly indicates not only the existence of such a difference, but also its causes and effect (larger body mass and longer life span). In contrast, the conventional narrative adopted to handle such a difference (based on the attribute/proxy variable 3,500 versus 2,200 kcal/day per capita) is simply providing an assessment that appears to be irrelevant to discuss these facts. That is, to achieve a longer life span you do not need more calories (more of the same), but a better quality diet. A better quality diet (with more animal proteins, fresh vegetables, fruits and safe drinking water) requires a significant increase in the biophysical cost of the diet. The “cost” of the diet can be represented in an integrated way, at the level of the society, by using a set of different indicators such as: labor requirement, land requirement, energy requirement, plus the economic capital requirement for supplying a high quality diet to a person over a year. When making the comparison using this set of indicators, the differences between the food system of a developing and a developed country become much larger. Depending on the chosen indicator the cost of the diet in developed countries, when considering either biophysical or economic quantifications, may be 10 or even 100 times higher than in developing countries. These dramatic differences between the two typologies of food systems are totally missed when adopting as indicator the difference in calories (60 %) indicated by the two benchmarks 3,500 versus 2,200 Kcal/day.

2.1.2 Describing the characteristics of the whole in relation to the characteristics of the parts: how to wisely blend extensive and intensive variables

As mentioned in the previous example, the flow-fund model proposed by Georgescu-Roegen (1974) for representing, in biophysical terms, the socio-economic process of production and consumption of goods and services distinguishes between *flow coordinates* and *fund coordinates* (for a more complete explanation of Georgescu's model see Mayumi 2001, chapter 6).

* *Flow coordinates* are elements that enter but do not exit the production process or, conversely, elements that exit without having entered the process (e.g., a new product). Flow coordinates include matter and energy *in situ*, controlled matter and energy, and dissipated matter and energy.

* *Fund coordinates* (Capital, People, and Ricardian land) are agents that enter and exit the process, transforming input flows into output flows. Fund coordinates can only be used at a specified rate and must be periodically renewed. Therefore, fund coordinates entail an overhead for their use and do entail a constraint on the relative rate of the flow coordinates associate with them.

The concept of a fund-flow model makes it possible to check whether or not an energy sector is viable in relation to the characteristics of the socio-economic process to which it belongs. In fact, an economic system can operate steadily as long as environmental flows of available energy and matter are made available by the energy sector to the other sectors, in the necessary amounts, and according to the set of constraints determined by the characteristics of the fund elements.

Building on the insight of Georgescu-Roegen's flow-fund model, the Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MSIASEM) approach provides a "bioeconomic" representation of the socio-economic process of production and consumption of goods and services. In fact, it makes it possible to address the biophysical constraints entailed by: (i) the characteristics of those economic elements guaranteeing the activities required for both production and consumption; (ii) the process of accumulation of capital; (iii) the process of adjustment of demographic variables, and (iv) the environmental loading resulting from the metabolism of society in relation to the supply and sink capacity of the ecosystem embedding it.

MSIASEM looks at the structure of the human economy in terms of the fund-flow relation over primary productive inputs. An example is given in Fig. 2a and Fig. 2b, in which the system of accounting is based on:

(1) Human Activity – which has the characteristics of a *fund element*, since it requires an internal investment of human activity for reproduction and maintenance. This determines a social and biophysical constraint on the supply of labor power. This fund element is measured in hours per year. The total budget of Human Activity represents, on the time scale of one year, the given endowment of hours for which the two complementing compartment of production and consumption compete;

(2) Exosomatic Energy – which has the characteristics of a *flow element*. The rate of exosomatic energy consumption in each sector can be assumed to map onto the level of economic activity, at a given level of technology. This flow is measured in Joules per year. The Total Energy Throughput represents, on the time scale of one year, the total energy dissipated by a socio-economic system for supporting the activities of production and consumption of goods and services.

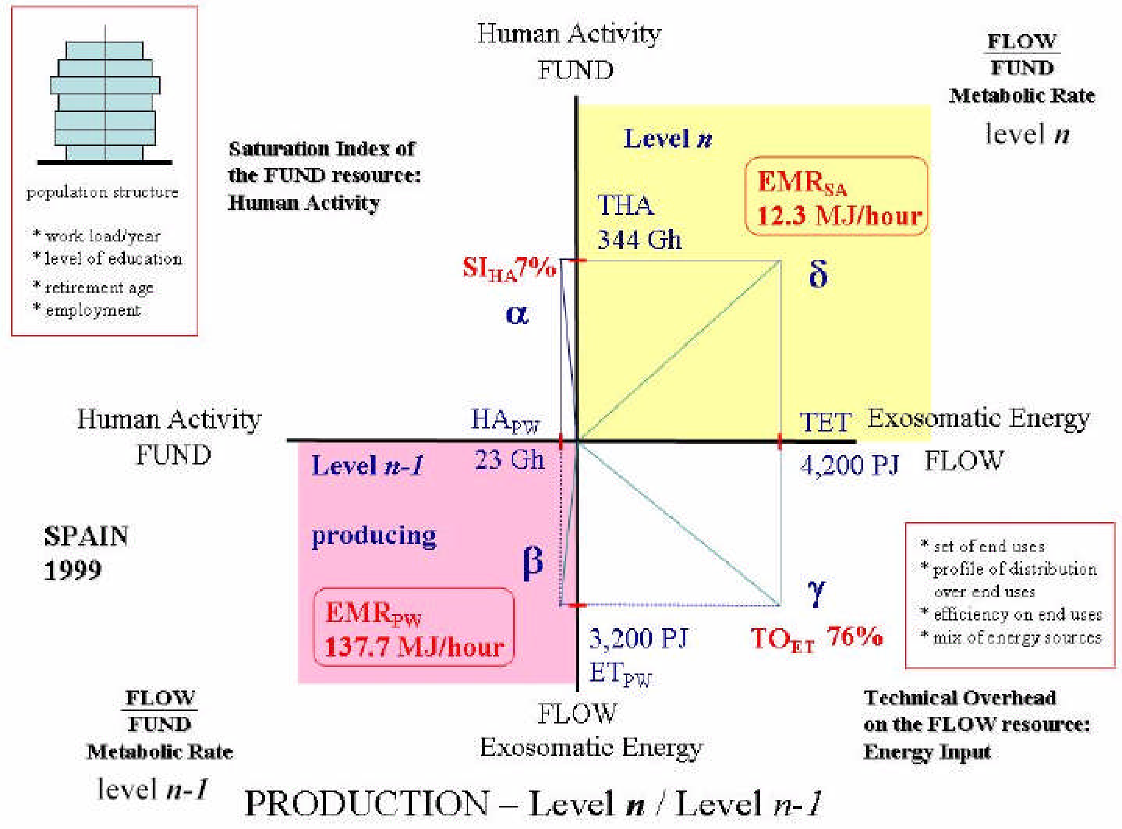


Figure 3a. Saturation index of human activity.

For more on the theoretical aspects of this approach see Giampietro and Mayumi, 2000a; 2000b; Giampietro, 2003; Giampietro and Ramos, 2005.

Getting into the method of accounting: (1) the fund variable - Total Human Activity (THA), the overall size of the fund resource - is equal to the maximum time available per person (24 hours x 365 days) multiplied by the population. THA is therefore a proxy for population size; (2) the flow variable - Total Exosomatic Throughput (TET) - is represented in "Joules equivalent" of a particular type of reference energy source (e.g. Oil equivalent) per year used by the economy. These two primary inputs are defined at the level of the whole socio-economic system (level *n*) in Fig. 2a (on the upper right quadrant with a yellow background). In this example referring to Spain in 1999 (data from Ramos, 2001), the value of THA is 344 Gh (Giga hours = billions hours, which is equivalent to the human activity expressed over a year by 39 million people), whereas the value of TET is 4,200 PJ (Peta joules = 10 to 15 joules) of exosomatic energy, which is the energy consumption, measured in Oil Equivalent, of that year. The value of the angle δ can be associated with the value of the Exosomatic Metabolic Rate of 12.3 MJ/h (MJ of exosomatic energy per hour of Human Activity) which was the Societal Average of the pace of exosomatic energy dissipation per hour of human activity in Spain in 1999. This value reflects the specific combination of production and consumption activities taking place in that economy in 1999.

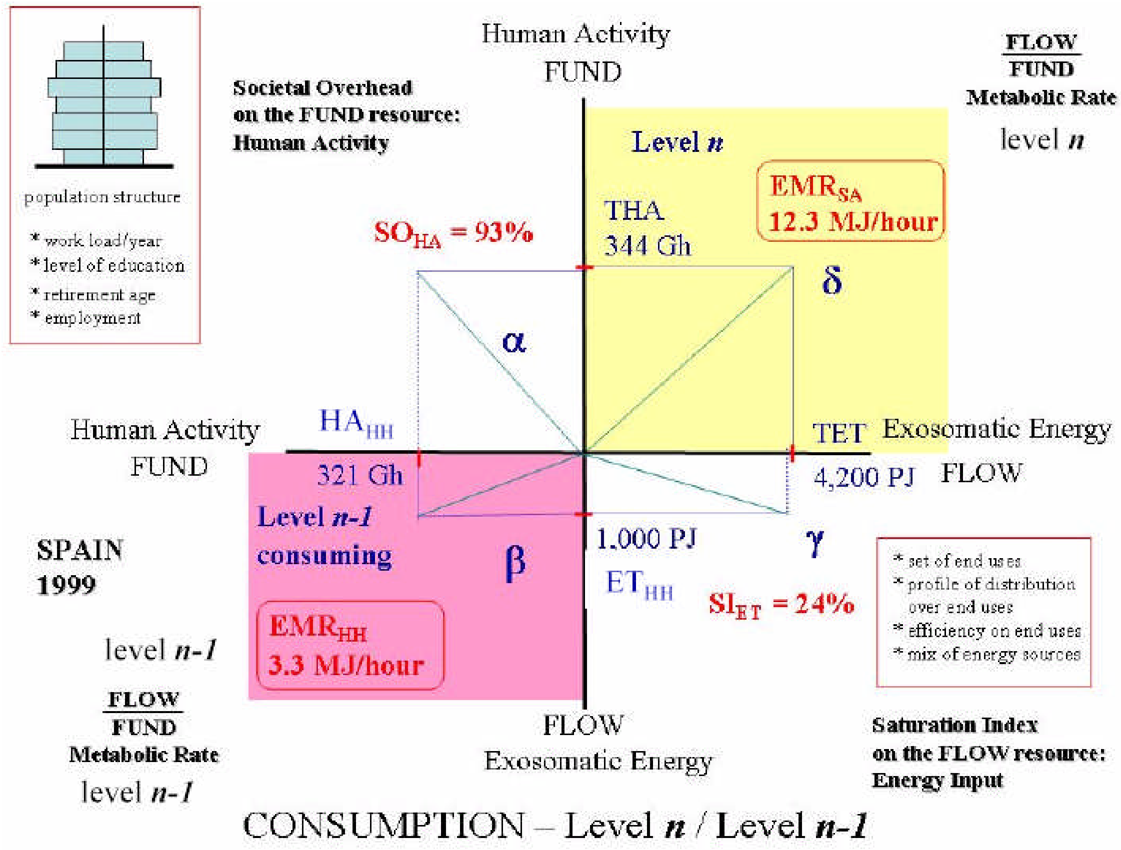


Figure 4b. Societal overhead for human activity.

The metabolism described in the yellow box as a combination of extensive variables - THA (fund) and TET (flow) -and intensive variable (EMR_{SA}) – the ratio of the two - can be disaggregated further – at the level *n-1* - into two lower level compartments:

(1) production – which is measured by the fraction of the total (both of Human Activity invested in the Paid Work sector – HA_{PW} - and Exosomatic Throughput in the Paid Work sector - ET_{PW}), and

(2) consumption – which is measured by the fraction of the total (both of Human Activity in the Household sector– HA_{HH} - and Exosomatic Throughput in the Household sector – ET_{HH}).

The two schemes presented in Fig. 8a and Fig. 8b *of the first paper of this series* do provide an overview of how it is possible to move across compartments defined at different hierarchical levels and establishing a link between the metabolic rate of the whole assessed at the level *n* and the metabolic rate of lower level compartments, assessed at the level *n-1.* Using the same rationale, in the example given in Fig. 2a, we have that – on the upper left quadrant - the total endowment of THA is reduced 93% because of the "overhead" operating at the societal level on the fund resource Human Activity (see also the dendogram of splits over the compartments of Human Activity given in Fig. 12 *of the first paper*). That is, the demographic structure (determining a given dependency ratio) and other socio-economic parameters (determining the work load of the economically active population) define the fraction of human activity which is actually invested in the Paid Work sector. In the same way, only a fraction of TET is actually invested in the productive sector. In this case, 76% of the TET has been used by Spain in the productive sector of the economy. After having calculated for the Productive Sector both the amount of Human Activity (HA_{PW} = 23 Gh) and the amount of Exosomatic Throughput (ET_{PW} = 3200 PJ), we can calculate for that sector the specific Exosomatic Metabolic Rate - $EMR_{PW} = ET_{PW}/HA_{PW}$ - which was in 1999 equal to 137.7 MJ/h of exosomatic energy per hour of human activity. This level of Exosomatic Metabolic Rate in production (at the *level n-1*) is much higher than the Societal Average (at the *level n*). Therefore, we can expect that the other sector associated with the split at the *level n-1*– that of consumption – has a lower metabolic rate than the Societal Average. This is confirmed by the analysis provided in Fig. 2b. The compartment of the socio-economic system dealing with consumption (the household sector) has a lower level of Exosomatic Metabolic Rate (EMR_{HH} = 3.3 MJ/h) than the societal average.

2.1.3 The link between metabolic compartments: the compartments in charge for production and consumption must compete over limiting fund resources

A simple look at the two set of relations presented in Fig. 2a and Fig. 2b clearly indicates a direct link over the values that can be taken by the two sets of intensive and extensive variables defining the metabolism of the two sectors in charge for production and consumption at the level *n-1*. This direct link is illustrated in Fig. 3. On the top, we have the three variables: (i) fund variable (THA); (ii) flow variable (TET); and (iii) the intensive variable determined by their ratio (EMR); all referring to the whole society – what we called the level *n*. On the bottom, we have the two sets of the same three variables [HA_i, ET_i, EMR_i], which are used to characterize the metabolism of the two sectors PRODUCTION and CONSUMPTION at the level *n-1*. The link is generated by the fact that the two angles – α and γ in Fig. 3 – which are used to calculate to the two levels of overhead on both Human Activity and Exosomatic Throughput on the two compartments of production and consumption are the complement of each other! That is, in order to calculate the reduction of the two extensive variables (fund and flows) when moving from the level *n* to the level *n-1* we can use in one case the tangent and in the other the cotangent of the same two angles. The two compartments of production and consumption – at the level *n-1* - compete for the same endowment of the total amount of the two fund and flow variables assessed at the level *n*. The existence of this direct link points at a key characteristic of the evolution of the metabolism of human societies. This peculiar characteristic has been addressed by Zipf (1941) when describing nations as “bio-social forms of organization.” Zipf gave a basic principle of socio-economic development: if a given economy wants to be able to produce more, it has to invest more in consuming. In his words, in a developed society, “leisure time becomes a key raw material for boosting the economy.” Here the concept of “investment” refers to the required amount of fund resources (human activity, technical capital and land), which have to be used either for producing or consuming more. The validity of such an idea was confirmed by the work of the Nobel Prize economist Stone (1961; 1985) when

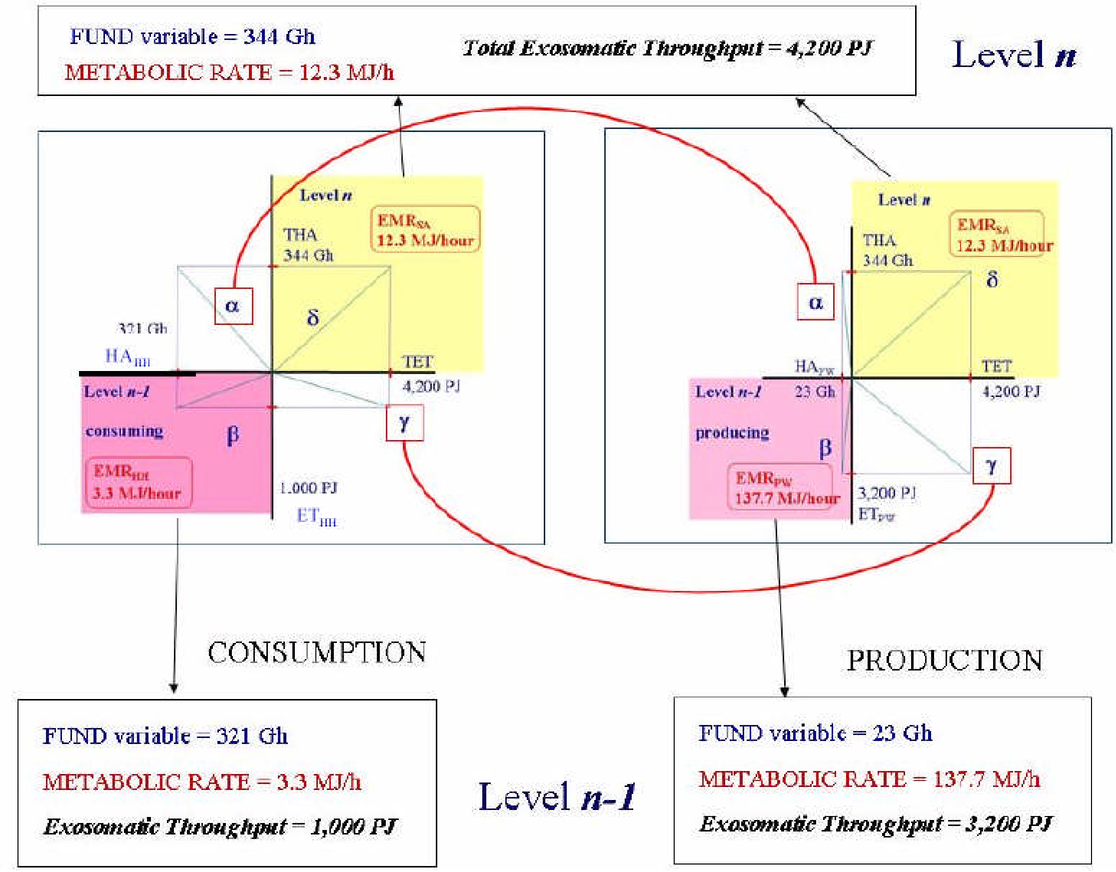


Figure 5. Total exosomatic throughput for consumption and production.

proposing a Social Accounting Matrix, dealing with the characterization of the final consumption sector. This sector can be used as a complement of the Input-Output Matrix of the type proposed by Leontief (another Nobel laureate in economics) to describe the interactions among the various economic sectors in charge for producing. As soon as the coupling is made, the two accounting matrices have to change in an integrated way during the process of economic development. This rationale implies that socio-economic development must be based on the ability of reaching a dynamic balance between investments of fund resources [Human Activity, Technical Capital – exosomatic machines - and Colonized land] over the two socio-economic compartments associated with producing and consuming.

2.1.4 Mosaic Effect: moving the analysis across multiple levels

The same rationale used when disaggregating compartments across levels (when moving from level *n* to level *n-1*), can be used to move from level *n-1* to level *n-2.* In this section we will provide an example of further disaggregation in relation to the compartment of Paid Work – as defined at the level *n-1*. The PW sector can be further disaggregated, at the level *n-2*, into three broad sub-sectors: (i) SG = services and government; (ii) PS = Productive Sector (which includes Manufacturing and Energy and Mining); and (iii) AG = agricultural sector (which include forestry and fishery). This can also be done for the household sector (e.g. dividing this sector between rural and urban households, and then by splitting them over different typologies of households), but it is not done here for reason of space.

When describing the exosomatic metabolism of a society across levels we can use the same approach used for studying the energy intake associated with the diet of a population (illustrated in Fig. 1). That approach describes human endosomatic metabolism of the whole population as resulting from a profile of distribution of human body mass over a given set of age classes, which are associated with different levels of metabolic rate. In the same way, we can describe the exosomatic metabolism of a given compartment of society as resulting from a given profile of distribution of human activity - expressed in "*hours of human activity*" as the equivalent of "*kg of human mass*" in Fig. 1 - over a set of economic sectors characterized by different Exosomatic Metabolic Rates (EMR_i) – the equivalent of the typical metabolic flow of different age classes. This approach is illustrated in Fig. 4a and Fig. 4b. These two representations provide a comparison of the changes that occurred in the exosomatic metabolism of Spain between 1976 and 1996. These changes are characterized using: (i) an extensive fund variable (the profile of HA_i in different compartments); and (ii) an intensive variable representing the ratio of the flow variable Exosomatic Throughput - ET_i - over the fund variable HA_i in the various compartments (EMR_i). By using this approach it becomes possible to visualize that when explaining the overall change in energy consumption of a given economy, changes in technical coefficients in different sectors ($\pm\Delta EMR_i$) are only a part of the story. The overall change in exosomatic energy consumption of a society does not depend only on the changes in technical coefficients (determining energy intensity in each compartment) taking place in its different compartments, but also on the changes in the profile of distribution of Human Activity over these different compartments.

A different way for representing the metabolism of a society which covers different levels, moving from level *n* to level *n-2* after splitting the sector PW, is given on the right side of Fig. 5a. We can either adopt the representation based on three bars of different size, for each of the three sub-sectors (SG; PS; and AG) the width of the bar is determined by the characteristics EMR_i of the sector *i* and the height of the bar is determined by HA_i (the amount of hours of the fund variable Human Activity). The extensive variable ET_i is then associated with the area of each bar. Within this system of representation the aggregated area of the 3 bars describing the 3 sub-sectors SG, PS and AG at the level *n-2* must be equal to the area of the bar representing the sector PW, at the level *n-1*. Alternatively, when adopting the representation based on the "4-angle figure," one can move from a level to another (in this example from level *n-1* to level *n-2*) by calculating the reductions of both funds and flow variables when moving across levels, according to their relative overheads (as done in Fig. 2 when moving from level *n* to level *n-1*).

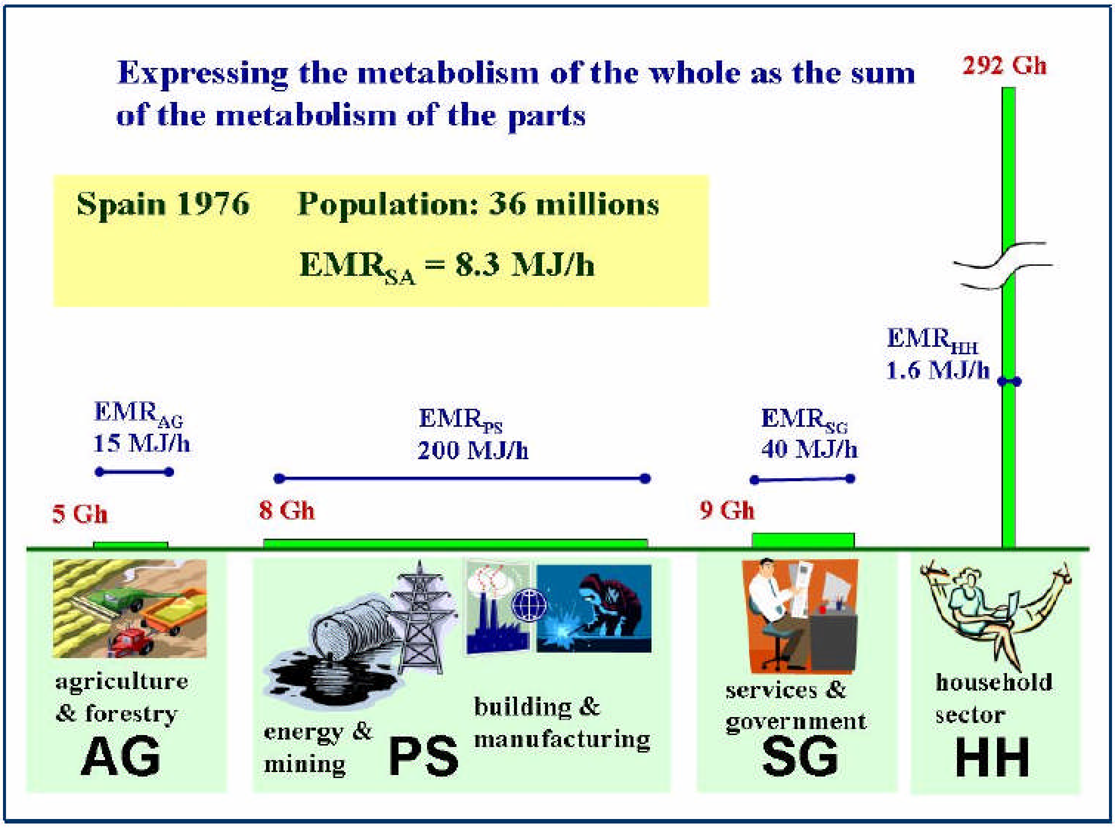


Figure 4a. Metabolism for Spain in 1976.

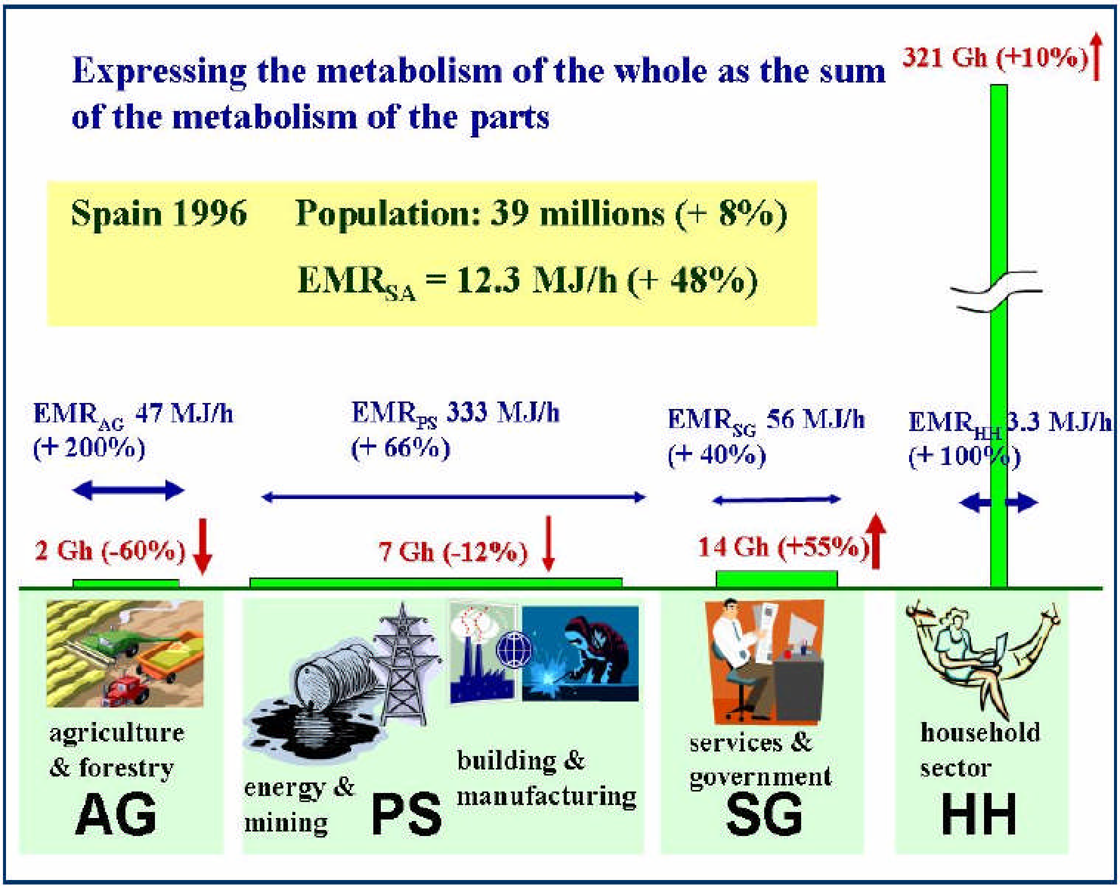


Figure 4b. Metabolism for Spain in 1996.

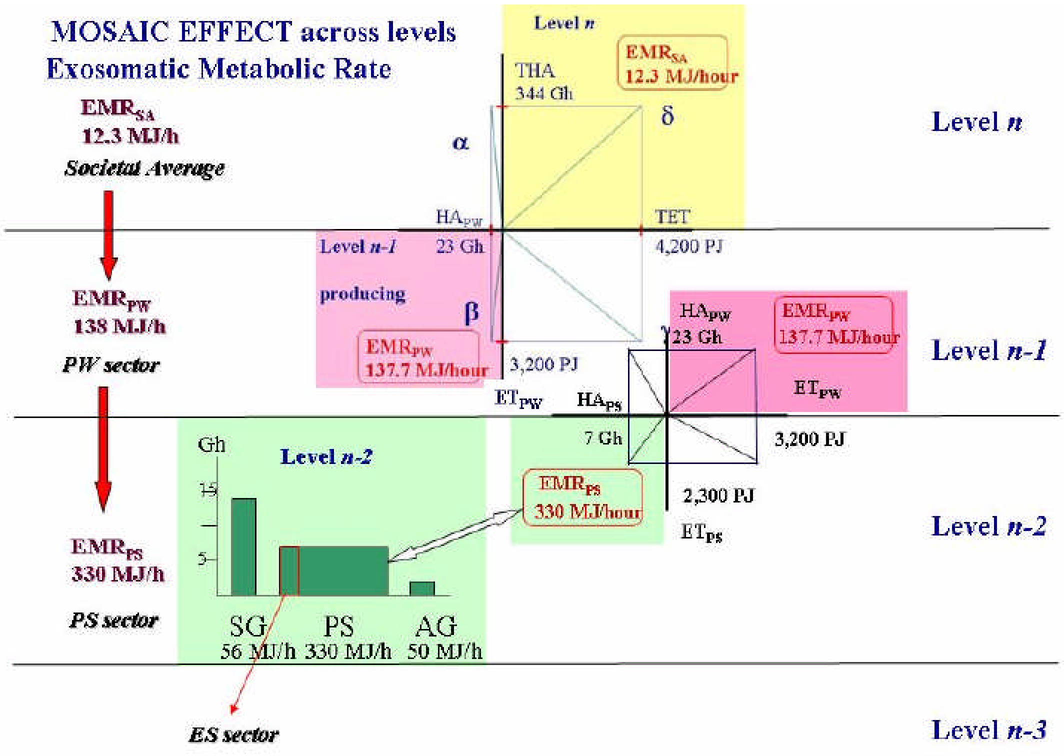


Figure 5a. A mosaic effect of exosomatic metabolic rate across levels.

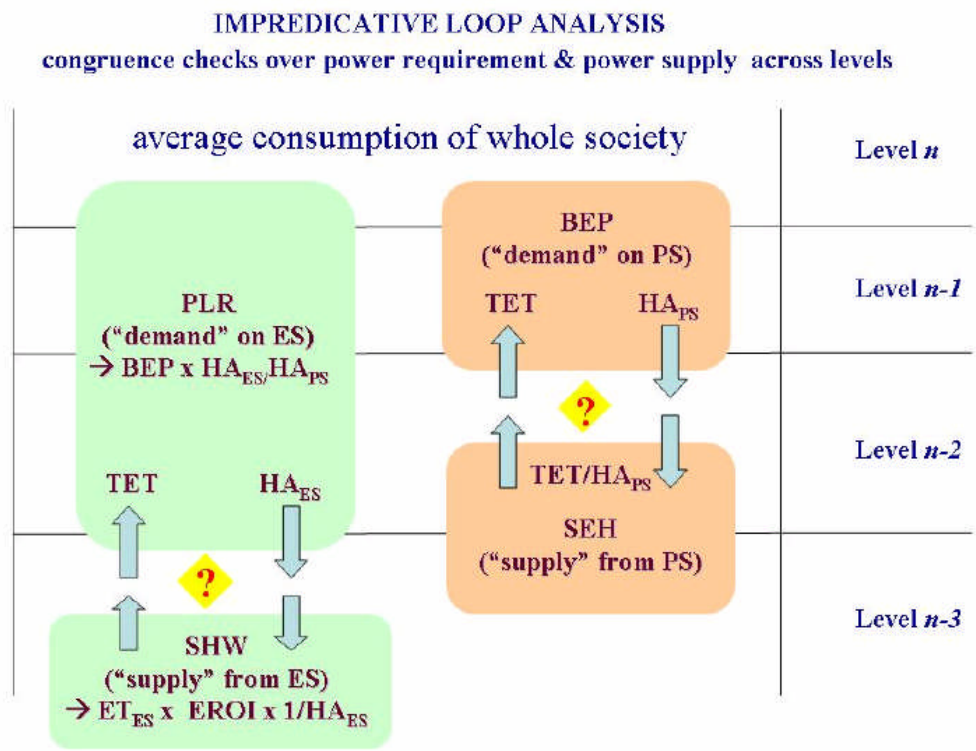


Figure 5b. Impredicative loop analysis.

2.1.5 Impredicative Loop Analysis: the forced congruence between the characteristics of the "expected" supply and the "delivered" supply of metabolic flows

In the first paper of this series we introduced the metaphor of the "heart" and "the rest of the body" as a way to verify the compatibility between the characteristics of the requirement of exosomatic energy from the energy sector. These "expected" characteristics are determined by the specific pattern of consumption of society (by the size and the metabolic rate of the compartment in charge for consumption); and the characteristics of the supply of exosomatic energy delivered by the energy sector, which are determined by the quality of energy resources and technological coefficients (determining the amount of working time and the supply of net energy per hour of labor in that sector). Therefore the check of this compatibility requires the ability to characterize the "demand" of society, which refers to the characteristics of the whole – defined at the level *n* - and "the supply" of the energy sector, which refers to the characteristics of one of the sub-sectors of the Productive Sector - at the level *n-3*. According to the system of accounting illustrated so far, this implies a jump over three levels of analysis: whole society as the level *n*; the Paid Work sector (related to the distinction Production versus Consumption) is the level *n-1*; the Productive Sector (related to the distinction Service and Government versus the set of activities stabilizing both the endosomatic and exosomatic metabolism), is the level *n-2*; and finally the definition of the Energy Sector, as a sub-sector of PS, is at the level *n-3*.

The second conceptual tool of MSIASEM that we present here is called *Impredicative Loop Analysis* (ILA). It has the goal of checking the congruence between: (1) the expected power level of the supply of a given flow (what is expected by "the rest of the body"), determined by the characteristics of higher level compartments; and (2) the actual supply per hour of work of that given flow (what is delivered by the sector in charge of the supply), determined by the set of conversions occurring in that sector. Therefore an ILA implies checking the feasibility of a dynamic budget in terms of the congruence between two characterizations referring to different hierarchical levels (for more see Giampietro and Mayumi, 2003b). That is, the characterization of a given metabolized flow - at the level *n* is non-equivalent to the characterization of the biophysical constraints determining the supply of such a flow at a lower level (at the level of the specialized compartment in charge for delivering such a supply). To avoid another long theoretical discussion let's use the self-explanatory example given in Fig. 6. As a matter of fact, the MSIASEM approach is very general and it can be used for studying different types of metabolized flows (e.g. energy, food, water, money). In this example, the ILA is applied to the "metabolism of letters" in a hypothetical society. The meta-model of analysis of ILA follows an approach similar to the Mosaic Effect in Fig. 5a. That is, on the top right quadrant we have a characterization of the metabolism at the level of the whole society: (1) the fund variable is human activity, related to a population of 1,000 people, which translated into a value of THA of 8.76 Mega-hours/year; (2) the flow variable is the amount of letters sent and delivered per year, which is 24,000; and (3) the metabolic rate (the ratio over the two) is equal to 2 letters sent per person per month, which result in a Mail Metabolic Rate of 0.003 letters per hour in this society (this is

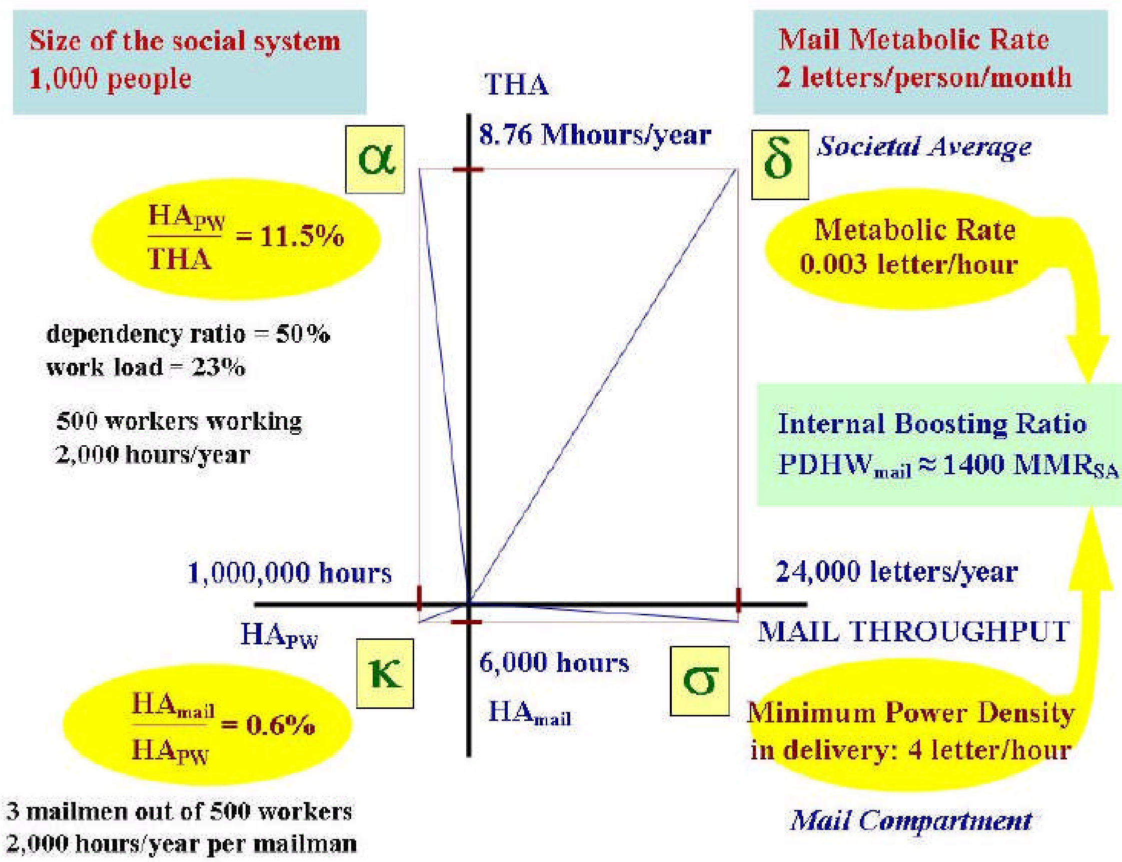


Figure 6. MSIASM approach for the post office.

indicated by the δ angle in the figure). The angle on the top, left quadrant - the α angle - indicates the reduction of Human Activity due to the split between production and consumption (associated with the ratio of HA_{PW}/THA). In this example only 11.5% of the total Human Activity is available for the sector Paid Work. The next angle to be calculated is the κ angle in the figure. Contrary to what done in an analysis looking for Mosaic Effect, when performing an ILA, this angle must include all the other reductions of human activities, which have to be summed, moving down through different hierarchical levels, to arrive to the special compartment in charge for guaranteeing the supply of the particular flow considered in the analysis. In this case, the overall reduction of working hours of Human Activity has to refer to the move from the PW compartment – all the hours of work in PW - to the "mail" compartment – the hours of work in the mail sub-sector. That is, the reduction refers to the ratio HA_{mail}/ HA_{PW}. This reduction entails that a limited supply of hours of Human Activity are available for the mail compartment. This value - 6,000 hours – is indicated in the lower vertical axes. Therefore, in a 4-angle graph referring to an ILA, the vertical lower axis refers still to hours of Human Activity. The lower angle on the right quadrant, the σ angle in the figure, indicates the level of power in the supply of letter (per hour of labor), which must be achieved in the mail sector - at the level *n-3* - given the series of reductions on human activity implied by the previous two angles. This power level is required in order to be able to guarantee the throughput of letter defined - at the level *n* - on the right top quadrant.

After illustrating this example of ILA, it is possible to explain the peculiar name chosen for this analysis. In fact, when working with this 4-angle figure there are two possible ways of handling the relative information.

#1 - we can look for the viability of a given scenario, by starting with a definition of hypotheses associated with the value of three angles. In this example, this would be: given a structure of the population and social rules (the value of the angle α), the actual profile of allocation of the work force over different compartments of the economy (the value of the angle κ), and a given value for the metabolism of letters (the value of the angle δ). Then this analysis can be used to determine what set of technical coefficients would be required (the value of the angle σ) to reach the compatibility over the dynamic budget determined by the characteristics of the requirement from "the rest of the body" and the characteristics of the supply from "the heart"; in alternative:

#2 - we can check whether or not in a given real system there is compatibility over the loop. Without this compatibility the system can either accumulate stocks of not delivered mail (if the power requirement is larger than the power supply) or not fully utilize the fund resources - mailmen sleeping during work time. That is, ILA can be used to check the severity of biophysical constraints in determining a given form of metabolism.

An example of an application of ILA to a real situation is given in Fig. 7 (from Giampietro, 2003). To show the extreme flexibility of this approach, also in this case, the ILA is not about energy flows for a country. Rather, this ILA deals with the money budget of a household in rural China. Moreover, this ILA is based on the simultaneous consideration of two different types of constraints associated with two type of fund variables: (1) colonized land – measured in hectares (Fig. 7a); and (2) human activity – measured in hours (Fig. 7b). In both cases, the metabolized flow by the household is "net disposable cash" (expressed in Yuan/household/year).

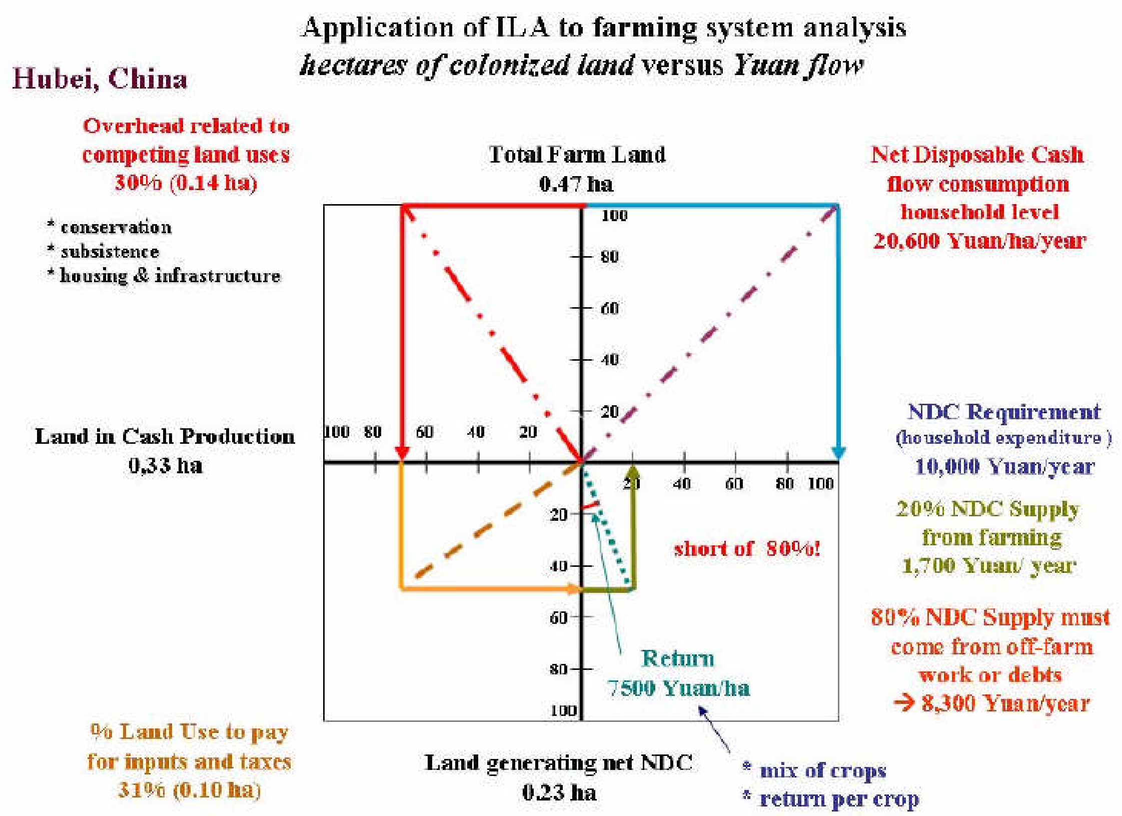


Figure 7a. Application of ILA to the agricultural system in Hubei, China

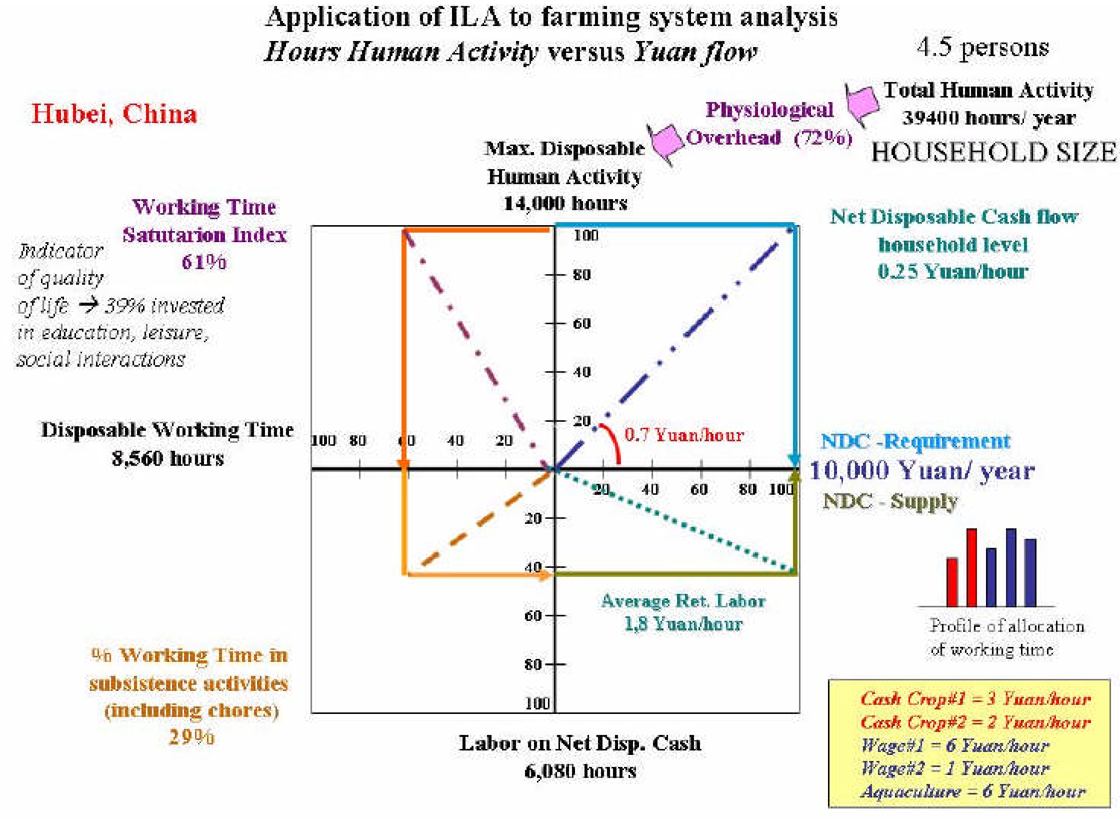


Figure 7b. Application of ILA to the agricultural system in Hubei, China using hours of human activity.

Looking at the graphs, the Metabolic Rate (referring to the angle δ in the two figures) is "Yuan/hectare/year" in Fig. 7a and "Yuan/hour/year" in Fig. 7b. Starting with the analysis referring to Fig. 7.a, there are two reductions over the total availability of land, when moving from the level *n* to the level *n-3* (the category of land use generating net disposable cash). These two reductions are indicated using the same two angles used in Fig. 6 (angle α and angle κ). In this example, it is clear that this household type is facing an extremely severe biophysical constraint in relation to land. Given the level of expenditures per hectare (20,600 Yuan/hectare/household) it is impossible to balance the budget of cash flow by relying on the supply of net disposable cash coming from the fraction of the total colonized land, which is invested in the category of land use: "cash crops." In fact this category of land use is generating a supply per hectare of 7,500 Yuan/hectare which is much smaller than the average consumption of 20,600 Yuan/hectare.

The same level of expenditure for the same household type can be studied in relation to a different dynamic budget, when mapping the flow of Net Disposable Cash against the fund resource "human activity" - Fig. 7b. The given flow of Disposable Cash spent by the household in a year entails an average Metabolic Rate for the household, assessed at the level *n*, of 0.25 Yuan/hour when considering THA. This metabolic rate becomes 0.7 Yuan/hour when considering this rate against the amount of hours of disposable human activity. The average economic return of labor (the net supply of Net

Disposable Cash made available to the household) associated with the category of human activity "work for cash," assessed at the level *n-3*, is 1,8 Yuan/hour. This value is much higher than the average level of expenditures per hour, assessed at the level *n*. This makes it possible to balance the dynamic budget, in spite of the chain of reductions, which are progressively limiting the supply of HA available for investment in the category "work for cash." However, this implies a minimum threshold of cash supply per hour for human activity invested in the category "work for cash." For a more detailed presentation of the study in China and the application of MSIASEM to farming system analysis, see Giampietro, 2003 – Chapter 11).

The examples provided so far clearly illustrate that when dealing with the process of self-organization of adaptive systems, it is impossible to determine a direction of causality over the loop. That is lower level characteristics may force changes over higher level characteristics – e.g. in relation to the ILA in Fig. 6 – in our hypothetical society continuous problems in the correct and cheap delivery of mail may result in a reduction of the overall exchange of letters at the level of the society; or in relation to the ILA in Fig. 7 - the inability to find more remunerative off-farm jobs can limit the level of cash expenditure of the household. Alternatively, higher level characteristics may force changes over lower level characteristics – e.g. in relation to the ILA in Fig. 6 - the firm commitment of the society to exchange more letters may result in a larger investment of either human activity (hiring more mailmen), capital (using better technology) and money (subsidizing the mail sector) in the mail sector; in relation to the ILA in Fig. 7 - the strive for a better standard of living can push some of the members of the household to emigrate to big cities looking for better jobs (changing the parameters defined at the level *n-3* in the short run), or to invest in the education of the children (changing the parameters defined at the level *n-3* in the long run).

In conclusion, in relation to ILA, it is important to keep in mind, that this system of accounting is not deterministic. That is: (i) different analysts can decide to quantify in different ways, the same meta-model used to represent the loop; and (ii) this meta-model cannot be used to make predictions about the future evolution of the dynamic budget. In spite of these limits, this approach still represents a very powerful tool for checking the feasibility of the dynamic budget of flows across levels and the reciprocal compatibility of the characteristics and size of the various compartments making up metabolic systems. Going back to Fig. 5 in relation to the analysis of the exosomatic metabolism of societies this figure provides two important messages.

The *mosaic effect analysis* given in Fig. 5a clearly illustrates that when moving to lower hierarchical levels tracking those compartments in charge for guaranteeing the exosomatic metabolism, there is a continuous jump in the level of Exosomatic Metabolic Rate per hour of human activity. At the level *n*, when considering all the activities averaged at the level of the whole society (production and consumption), EMR_{AS} is 12.3 MJ/h. At the level *n-1* when considering only the Paid Work Sector (only those activities generating added value), EMR_{PW} becomes more than 10 times higher – 138 MJ/h. At the level *n-2*, when considering only the Productive Sector (guaranteeing those activities in charge for generating the physical inputs for the metabolism of society), EMR_{PS} becomes

330 MJ/h. In fact, the PS sector includes building and manufacturing, which is about making exosomatic infrastructures and machines. This implies that the pace of the exosomatic rate per hour of work is more than doubled when moving from PW to PS.

The Impredicative Loop Analysis in Fig. 5b illustrates two possible "congruence checks" which can be performed across different hierarchical levels referring to the viability of the dynamic budget of the societal metabolism. The power levels per hour of work of the "expected supply" and "delivered supply" of exosomatic energy can be defined on different interfaces. It should be repeated here that these checks are not about the compatibility over: (i) Exosomatic Metabolic Rates, and (ii) size of the relative compartments (the approach followed when looking for the Mosaic Effect across levels). Rather they refer to the congruence between: (i) the flow per hour expected from the "rest of the body"; and (ii) the flow per hour delivered "by the heart." Indicated in Fig. 5b are two checks referring to two different definitions of "rest of the body" and "heart" associated with two definition of the supply of exosomatic energy.

The first check is about an expected power level called Bio-Economic Pressure (BEP), which has to be matched by the power level in supply, called the Strength of the Exosomatic Hypercycle (SEH) on the interface "whole society" versus "PS sector." This refers not only to the delivery of energy carriers (e.g. fuels and electricity), but also to the delivery of exosomatic devices and technical infrastructures. The second check is related more directly to the Energy Sector and entails that the Expected Power Level (EPL) of the supply of energy carriers associated with a given socio-economic structure, must be matched by the actual Supply per Hour of Work (SHW) achieved in the energy sector. A more detailed analysis of these two congruence checks is discussed in Section 3.

3. Changes across compartments defined on different levels must be congruent over the whole loop: implications for the energy sector

3.1 The Bio-Economic Pressure

The dynamic relation among the characteristics of the metabolism of the whole and the characteristics of the metabolism of the parts can be associated with the concept of Bio-Economic Pressure (BEP). The reference to pressure wants to indicate that the growing metabolism of the whole (at the level *n*) associated with economic development entails qualitative transformation in the pattern of the exosomatic metabolism. The productive sector is producing more goods at the same moment in which a larger fraction of human activity is invested in consumption. This translates into a required boost over the pace of the throughputs per hour of human activity in the compartment of production (at the level *n-1*). This pressure will increase further in those sub-compartments in charge for the supply of biophysical flows – the productive sector (at the level *n-2*) – and in particular for those compartments specialized for the supply of endosomatic and exosomatic energy carriers: the energy sector and the agricultural sector (at the level *n-3*).

By adopting the MSIASEM approach it becomes possible to study the effect of the Bio-Economic Pressure at different levels, by establishing a link between different sets of variables that have to be changed in an integrated way to achieve congruence over an impredicative loop (across compartments operating at different levels). In plain words the bio-economic pressure can be defined as the need of controlling a huge amount of energy in the productive sector PS, while reducing as much as possible the relative hours of work requirement. In fact, the PS sector is in charge for the stabilization of the whole exosomatic energy consumption of society associated with TET, but it has to do that while using only a small fraction (HA_{PS}) of the available human activity (THA). Economic development entails an increase in the flow of energy consumed (TET) and a smaller fraction of THA available in PS (HA_{PS}), therefore it implies a boost in the value of BEP (= TET/ HA_{PS}).

The forced relation over TET and HA_{PS} can be formalized in different ways using different sets of variables, as indicated in Fig. 8 (for more details on the set of possible formalizations to be used in this approach see Giampietro and Mayumi, 2000a; 2000b). Very briefly, the graph on the top of Fig. 8 shows the ILA defining BEP. This definition is associated with the double reduction of THA limiting the amount of hours that can be invested in PS. This double reduction implies an Internal Boosting Ratio (on the interface level *n* (Exosomatic Metabolic Rate of the society as a whole) and level *n-2* (the PS sector) of more than 26/1. That is, in the top graph we are looking at the definition of BEP as the "expected" power level of the supply of exosomatic energy from the rest of society. This pressure is determined by the average level of consumption (assessed at the level of the whole society) and the profile of allocation of human activity over the different compartments of the socio-economic systems. As noted earlier, we can look at the same value (TET/HA_{PS}) from a different perspective. We can look at the definition of the "delivered" power level, which is determined by the technical coefficients achieved within the PS sector. We can study that by using the concept of Mosaic Effect Across Levels. This is illustrated in the lower graph of Fig. 8. This graph is similar to the one provided in Fig. 2a, with the only difference that when adopting a strict biophysical definition of "production" and "consumption," the Service and Government sector (even if producing added value in economic terms) has been considered as a net consumer of both exosomatic energy and other physical goods. Therefore, in this analysis it is aggregated together with the HH sector in a large compartment which is a net consumer of exosomatic energy (and exosomatic devices and technical infrastructures).

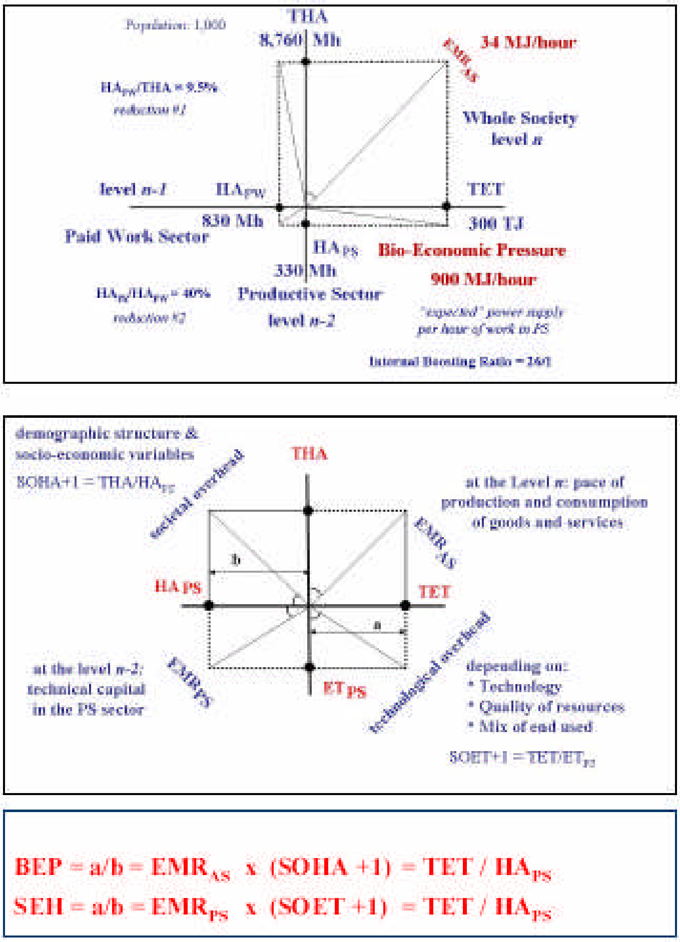


Figure 8. Mosaic effect across levels.

The two equations of congruence written on the bottom of the figure entail that the values of the variables and parameters determining both BEP and SEH have to change in a coordinated way in order to establish a feasible dynamic budget. Even if this approach is not deterministic, still it provides a set of rigorous constraints on the feasibility of exosomatic dynamic budgets characterized in this way. The popular game of SUDOKU can be recalled here to provide an analogy. SUDOKU entails a multi-level set of constraints over the possible values which can be entered into its system of accounting. The SUDOKU system, at the beginning, is not deterministic (both in the dimension of the grid and in the choice of the initial set of numbers to be used as an input). However, after: (i) having decided the structure of the grid; and (ii) entering a certain amount of numbers, the remaining numbers must result congruent with the constraints determined by the grid size and the numbers already in.

In the rest of this Part 2 we will provide examples of application of the MSIASEM approach that confirm the validity of the following three hypotheses:

> * Hypothesis #1 – looking at the structure of societal metabolism of different countries of the world, the forced relation of congruence in terms of Impredicative

Loop Analaysis and Mosaic Effect Across Levels entails an expected relation between: (i) the values of EMR_i at different levels; (ii) the values of the two overheads: on the supply of human activity (the fraction of human activity, which is not available for the productive sector, because it is required by HH and SG), and on the supply of technical capital (the fraction of exosomatic throughput, which is not available for final consumption, because it is required by the productive sector);

* Hypothesis #2 – because of the constraints associated with the "mosaic effect," when writing a series of relations over variables belonging to different disciplines and referring to different hierarchical levels of analysis, the values of these variables can only change in a coordinated way. Therefore, in an empirical study of these values over different countries in the world, we should find that this correlation over variables referring to different disciplinary fields hold.

* Hypothesis #3 – it is possible to use the MSIASEM approach to generate a formalization of the metaphor of the required compatibility between "the heart" and "the rest of the body." That is, MSIASEM is a system of accounting capable of characterize, in quantitative terms, the exosomatic energy requirement of society over the PS compartment, using the two non-equivalent formalizations: (1) BEP as the image of the expected performance of the heart, as seen from "the rest of society"; and (2) SEH as the expression of the characteristics of the supply from the PS sector, as seen from "the heart." Within this given formalization, then, it becomes possible to look at the factors determining the compatibility between these two values. At the level of the Energy Sector it is possible to define another two non-equivalent formalizations: (1) an Expected Power Level (EPL_{ES}), which is relative to the supply of energy carriers that society is expecting from the energy sector; and (2) the Delivered Power Supply (DPS_{ES}), which is relative to the actual supply of energy carriers from the energy sector to society.

3.2 Check of Hypothesis #1

If the rationale of the MSIASEM approach is true THEN when performing an empirical analysis over the characteristics of the metabolism of different world countries at different levels of economic development, we should find that:

#1 the value of BEP should correlate well with the conventional indicators used to describe the different levels of socio-economic development.

#2 the values of the benchmarks associated with the different angles (EMRi) and with the overheads (the two complementing angles) should vary in a coordinated way when moving across socio-economic system at different levels of development (when moving across different typologies of metabolism).

3.2.1 The correlation of BEP with indicators of development

Such a check was done (Pastore et al, 2000) on a database which includes 107 countries, comprising more than 90% of world population. The study included 24 conventional indicators of material standard of living and development (a selection basically reflecting the set of indicators found in World Bank Tables) divided into three groups:

(i) seven indicators of economic and technological development;

(ii) eight indicators of nutritional status and physiological well being;

(iii) nine indicators of social development;

The result of this empirical analysis validated the hypothesis. In fact, BEP shows a good correlation with:

(i) all classic economic indicators of development;
* average value of r = 0.88 (ranging from 0.77 to 0.92).

(ii) all nutritional status and physiological well being indicators;
* average value of r = 0.78 (ranging from 0.65 to 0.87).

(iii) all health and social development indicators;
* average value of r = 0.76, (ranging from 0.44 to 0.89).

A graphical overview of the relationship between BEP and the indicators used by the World Bank is given in the upper part of Fig. 9. The fact that the various points are clearly following a coherent pattern supports the hypothesis.

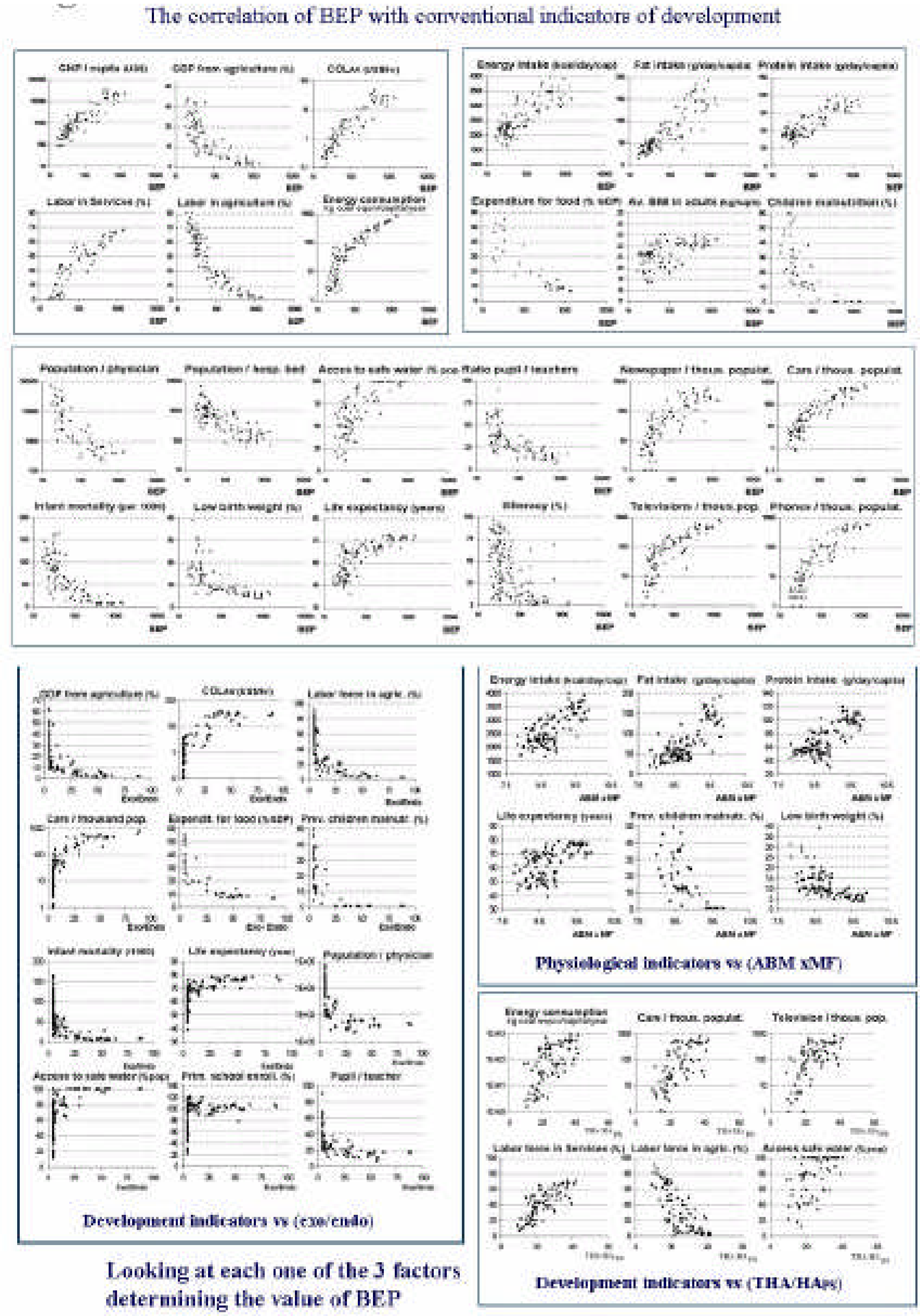


Figure 9. Correlating BEP with development indicators.

3.2.2 Using EMR_i and ratios over fund-variables as benchmarks for comparison

An overview of values of the various benchmarks characterizing the exosomatic metabolism for different typologies of countries is given in Fig. 10. For example when looking at EMR_{PW} (on the vertical axis) and EMR_{HH} (on the horizontal axis) we look at: (i) the level of biophysical capitalization of the PW sector (the amount of technical devices and fossil energy inputs used to boost the productivity of a hour of human activity invested in this sector); versus (ii) the level of biophysical capitalization of the HH sector – HH is the compartment in charge for the final consumption of goods and services. For example, non-OECD countries have a low level of capitalization for both the PW and HH sector, whereas a few countries such as USA and Canada have a level of capitalization above the OECD average for both sectors. Other developed countries such as Italy, Spain and Japan have a level of capitalization in the average of the rest of OECD countries (when eliminating from the group USA and Canada). Alternatively, it is possible to look at the angles related to the overheads – e.g. the ratio between working and non-working human activity, which is a function of the angle α. In the example given in Fig. 10 the numbers written on the horizontal axis (the value goes from 5 to 19) represent the ratio between the hours that, within a given society, are spent in consuming per each hour spent in producing. To give a practical example, China, due to the enormous work load (per worker) and a very low dependency ratio has a very small overhead on the supply of one hour of labor to the PW. That is, investing a hour of human activity in PW implies (has a biophysical cost of) having 5 hours of human activity invested in consumption. On the other extreme the characteristics associated with the value of the α angle in Ecuador implies that the supply of one hour of labor to the PW sector implies (has a biophysical cost of) 17 hours of human activity invested in consumption. By knowing the various factors determining the value of this reduction (or the α angle) we can look for explanations behind these differences. In Ecuador, for example, the problem is related to the country's very young population (because of the baby boom associated with the discovery of oil there and because of massive doses of emigration), in China to the aggressive policy of birth control enforced in the past.

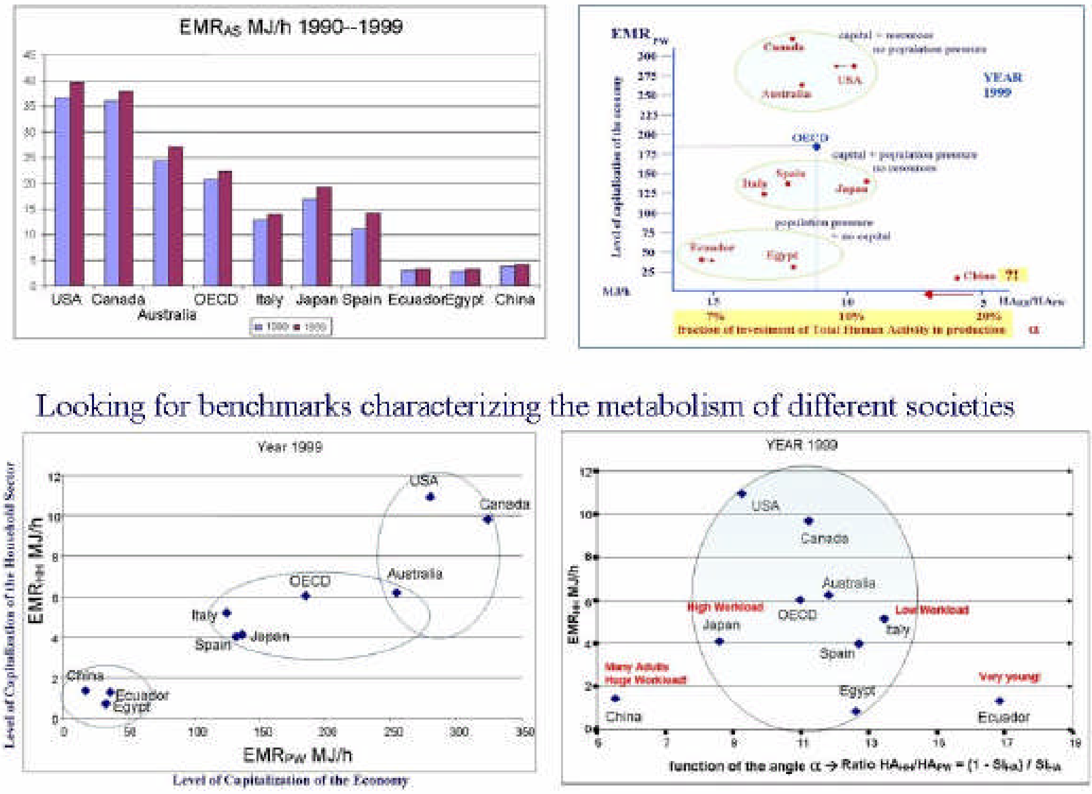


Figure 10. Metabolism benchmarks for different societies.

Finally, this brief overview of the possibility of using this approach for comparing the different metabolic patterns of different types of countries is closed by Fig 11 (Ramos, 2005), where the basic 4-angle analysis is used to provide a comparison of the characteristics of the *exosomatic metabolism* of OECD countries (in green) and the characteristics of the *exosomatic metabolism* of China (in red) in the year 1999. In this comparison we can see that the two socio-economic systems do have a similar size in terms of THA (i.e. population size - almost 10 Gh China and almost 11 Gh the cluster of OECD countries). However, they are very different in relation to the metabolized flow of exosomatic energy. The value of TET is almost 220 Exa Joules for OECD countries versus 45 Exa Joules for China: a difference of almost 5 times. This would imply that if China - plus India and other developing countries - would follow the same path of development of OECD countries (moving toward the same set of characteristic benchmarks for their exosomatic metabolism) we should expect an increase of several times in the aggregate emissions of carbon dioxide. In this case, it is the particular demographic structure of China (the side effect of an aggressive birth control enforced in past decades) which entails a very unusually low dependency ratio (only 40% of dependent population). This peculiarity is coupled to another peculiarity - an unusually high workload per year for workers (2,820 hours/year). This combination implies that current percentage relative to HA_{PW}/THA is more than the double in China (18.4%) than the value (9.1%) found in OECD countries.

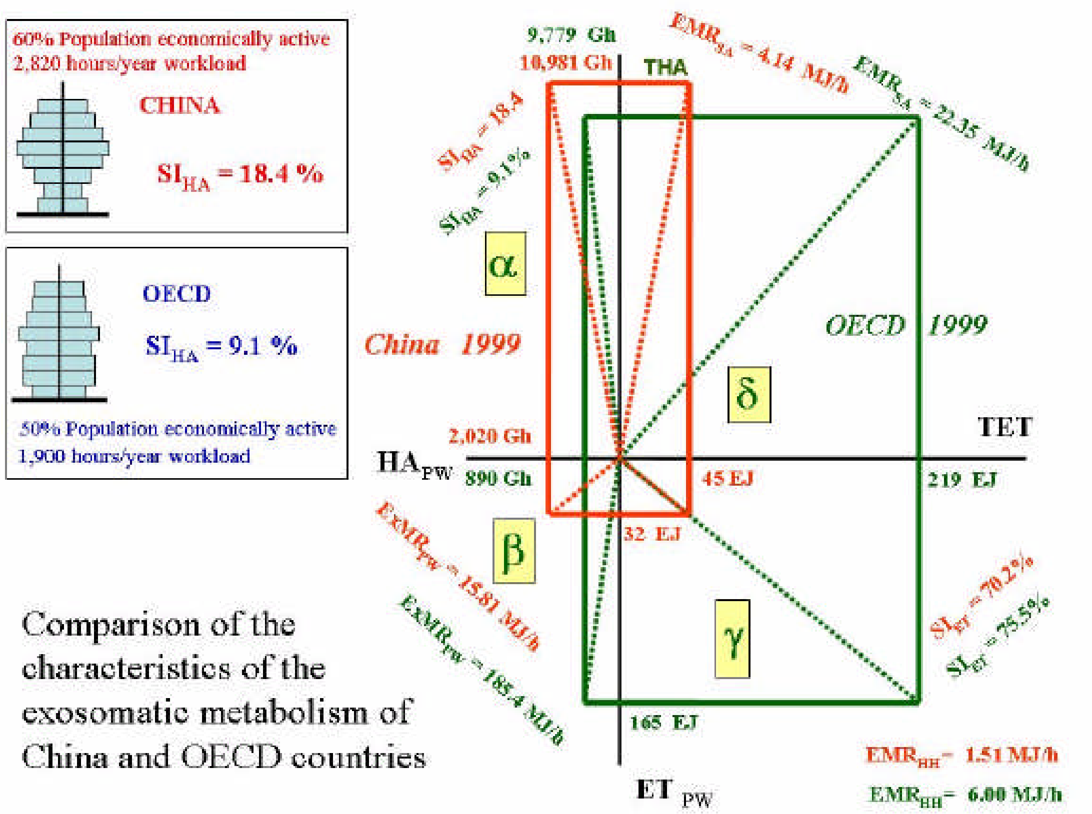


Figure 11. Comparison of exosomatic metabolism for China and OECD countries.

This provides China a clear advantage for labor intensive economic exports in relation to other economies (Ramos, 2005). However, this situation is: (i) temporary (when this cohort of workers will age, China will have a high level of elderly in its population); and (ii) determining harsh conditions for the material standard of living in the HH sector. In fact, the large flow of adults entering into the SG and PS sectors (determined by the huge flows of rural adults getting away from the AG sector) requires that all the surplus generated by the Chinese economy be reinvested there (in producing paid job within PW), rather than used to improve the level of consumption of the household sector (in consuming in HH).

3.3 Check of Hypothesis #2

Another possible application of the concept of the Mosaic Effect is illustrated in the top part of Fig. 12. Using this rationale it is possible to write identities based on variables relative to non-equivalent characterizations of Societal Metabolism. The example given in Fig. 12 is TET = endo x "exo/endo" (Total Exosomatic Throughput is equal to the Endosomatic throughput multiplied the ratio Exosomatic/Endosomatic metabolism). Because of their redundancy these identities can appear useless. However, as illustrated in the examples of data sources listed in Fig. 12, the same term can be estimated using non-equivalent data sources (the reader can recall here also the example of the metabolism of population discussed in Fig. 1). This implies that due to the redundant

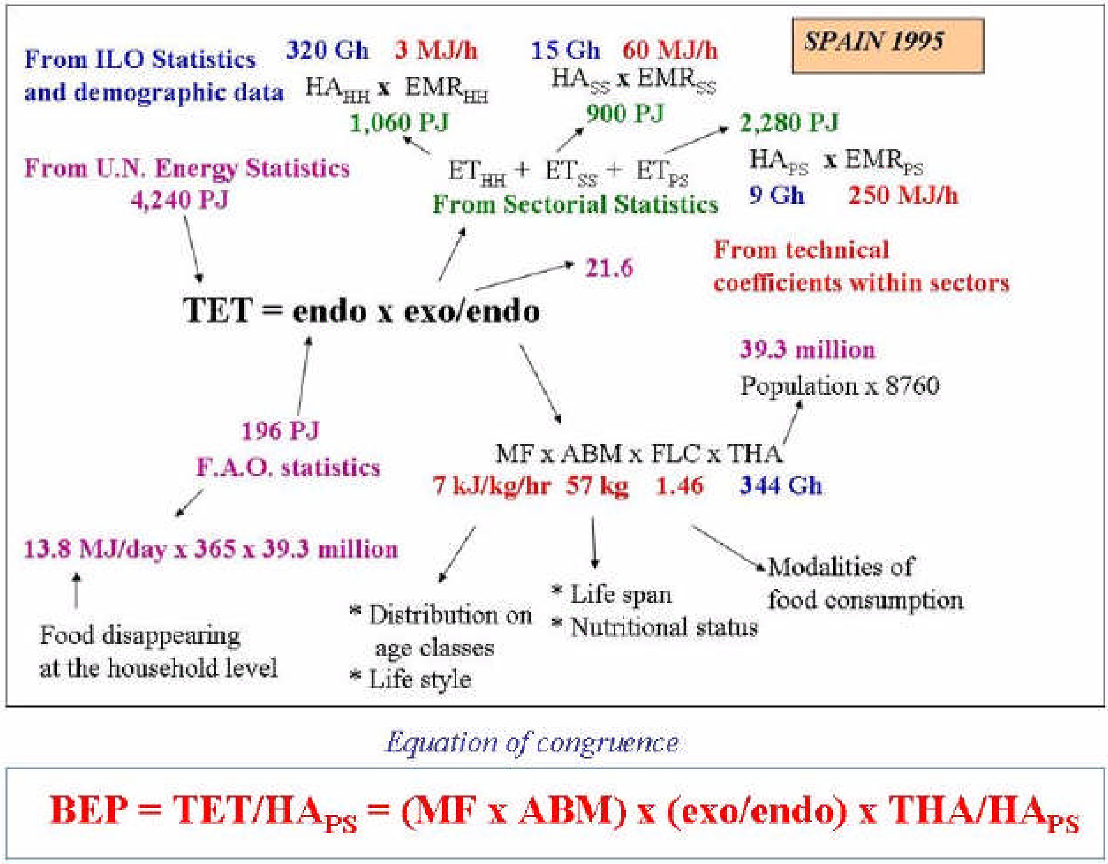


Figure 12. Explanation of TET and BEP.

structure of relations we should expect that the values of these variables have to change in a coordinated way, in order to maintain the overall congruence over the system of accounting. Due to the availability of non-equivalent data source we can check this hypothesis. As a matter of fact, using this rationale it is possible to write the value of BEP as a combination of three different factors:

$$BEP = [ABM \times MF] \times \text{“exo/endo”} \times [THA/HA_{PS}] = TET/HA_{PS}$$

(i) [ABM x MF] is the first factor in which “Average Body Mass” (in kg) and Metabolic Flow (in MJ/h of food energy per kg) are variables referring to human physiology;

(ii) [exo/endo] is the second factor and refers to the ratio between the energy metabolized outside the body (exosomatic energy) and that metabolized inside (food energy). In practical terms, due to the relative stability of the value of “endosomatic flow” in comparison with “exosomatic flow,” this ratio is a proxy of the overall consumption of commercial energy for producing and consuming goods and services (it correlates very well with GDP);

(iii) [THA/HA_{PS}] is the third factor which reflects social characteristics (demographic structure, level of education, retirement, work load, etc), determining the split of human activity between short term tasks (PS sector: producing goods and supplying energy) versus tasks relevant in the long term (SG&HH sectors: producing and improving the quality of the supply of the fund resource human activity).

Therefore the variables determining the value of each one of these three factors are reflecting three logically independent descriptions of the effects of development, which are based on the adoption of different scales and scientific disciplines. However, the very good correlation of the value of BEP with indicators of development does indicate the existence of a link across levels and discipline which is determining that with economic development all these variables change in a coordinated way. As a matter of fact, it is well known that, for socio-economic systems, different levels of economic development can be related to different stages of the demographic transition. As illustrated in Fig. 13 the relative differences in the structure of population will entail a

Correlation between BEP, EXO/ENDO ratio, THA/HAPS, ABM x MF and major indicators of nutritional status, physiological well being:

	log (BEP)	log(Exo/Endo)	THA/HAPS	ABM x MF
	r	r	r	r
Life Expectancy	0.79	0.75	0.63	0.59
Energy intake	0.82	0.81	0.55	0.73
Fat intake	0.87	0.85	0.63	0.77
Protein intake	0.85	0.85	0.57	0.72
Children malnutrition	-0.71	-0.65	-0.63	-0.70
Infant mortality	-0.76	-0.74	-0.57	-0.58
Low birth weight	-0.65	-0.62	-0.49	-0.63

Correlation between BEP, EXO/ENDO ratio, THA/HAPS, ABM x MF and some major indicators of economic and technological development:

	log (BEP)	log(Exo/Endo)	THA/HAPS	ABM x MF
	r	r	r	r
Log(GNP)	0.92	0.89	0.63	0.66
% Agric. on GDP	-0.77	-0.73	-0.60	-0.54
Log(COL_{AV})	0.92	0.87	0.71	0.63
%Lab.force in Agric	-0.90	-0.81	-0.72	-0.66
%Lab.force in Serv.	0.90	0.83	0.76	0.56
Energy cons/cap	0.92	0.95	0.53	0.67
Expendit for food	-0.86	-0.87	-0.69	-0.78

Correlation between BEP, EXO/ENDO ratio, THA/HAPS, ABM x MF and major indicators of social development:

	log (BEP)	log(Exo/Endo)	THA/HA_{PS}	ABM x MF
	r	r	r	r
Televis./ inhab.	0.89	0.89	0.62	0.72
Cars / inhab.	0.88	0.91	0.59	0.72
Newspap / inhab	0.77	0.80	0.47	0.60
Phones / inhab.	0.87	0.88	0.61	0.71
log(pop./physician)	-0.81	-0.76	-0.60	-0.67
log(pop./hosp.bed)	-0.77	-0.78	-0.51	-0.70
Pupil/teacher	-0.77	-0.76	-0.51	-0.62
Illiteracy rate	-0.61	-.058	-0.42	-0.44
Prim. school enroll.	0.44	0.39	0.38	0.36
Acces to safe water	0.78	0.77	0.53	0.59

Figure 13. Correlations between BEP, Exo/Endo ratio, THA/HAPS, ABM*MF, and indicators of economic, social, and technological development.

different distribution of individuals over the two categories of human activity "working" and "non-working." Moreover, if the specific distribution of individuals over age classes is corrected for the relative value of body mass (measured in kg per individual) – as illustrated in Fig. 13 – it is easy to realize that also physiological variables (Average Body Mass and Metabolic Flow of endosomatic energy) are affected by these changes (Giampietro et al. 1993). When considering the correlation of each one of the three factors with BEP (shown in the lower part of Fig. 9) over the major indicators of development, we find that each one of these three factors works well as indicator of development. They work well also in relation to those indicators of development more related to their disciplinary field as illustrated by the tables given in Fig. 14.

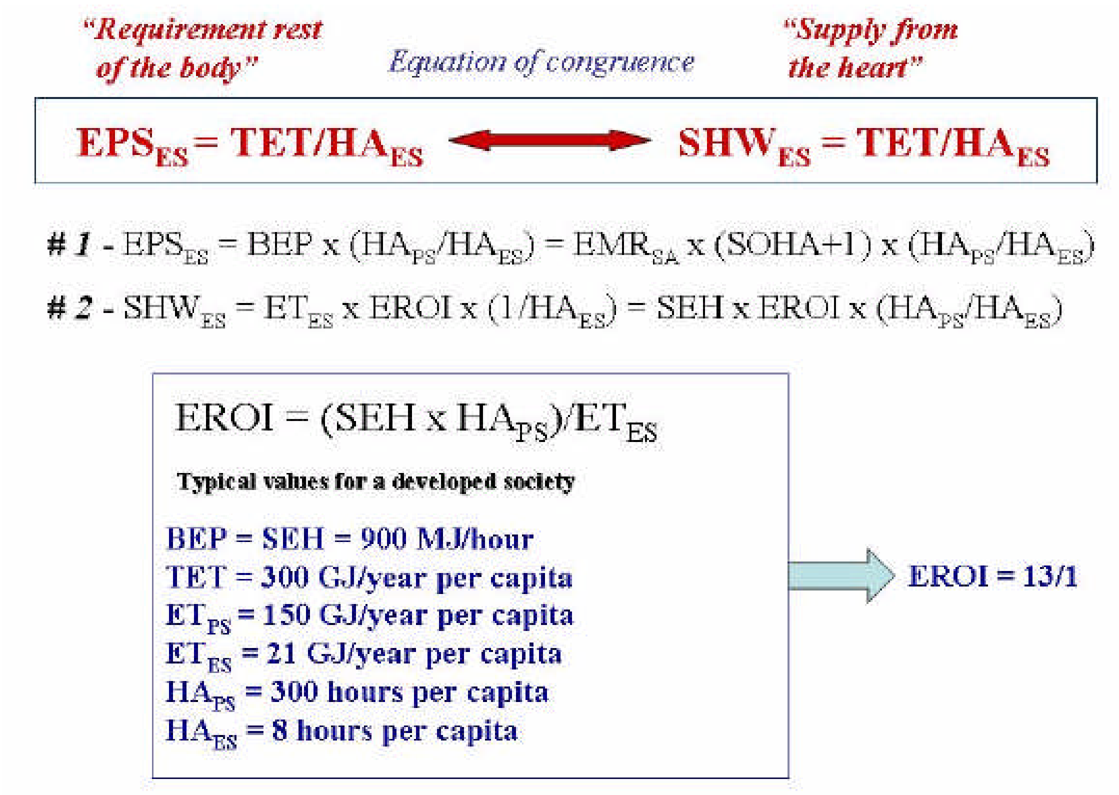


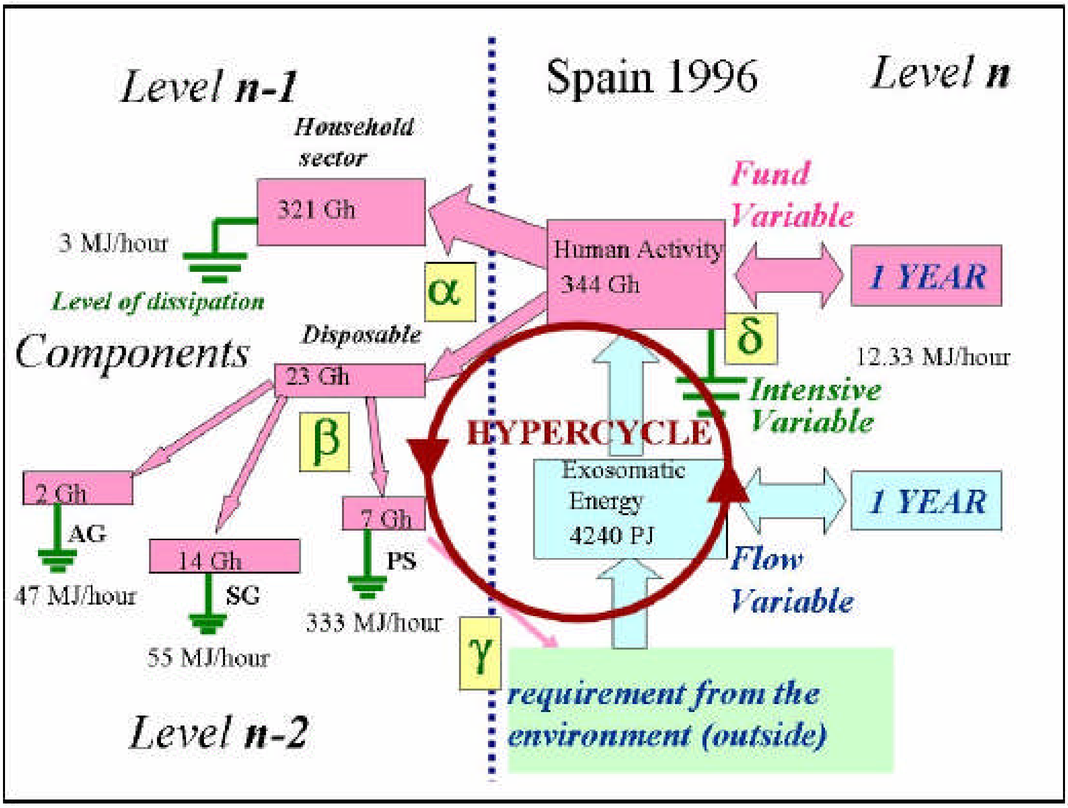
Figure 14. Characteristics of the energy sector.

3.4 Check of Hypothesis #3

As discussed in Fig. 5b, ILA can be used to define the difference in the pace of the flow between: (i) the average level of consumption of a given flow at the level *n* (the whole society); and (ii) the power level at which specialized sectors in charge for making available that biophysical flow to society (e.g. agricultural sector, energy sector) - at the level *n-3* – has to deliver its supply. That is, an ILA defines an Internal Boosting Ratio determined by: (i) the "demand" of society for a given flow (how much the society is willing to consume and how much human activity and other fund resources is willing to invest in the relative compartment) at the level *n*; and (ii) the "supply" of the specialized sector in charge for making available that flow (how much flow can be delivered per unit of investment of human activity and other fund resources) at the level *n-i*.

As illustrated in the upper part of Fig. 8 the Bio-Economic Pressure on PS can be associated with an Internal Boosting Ratio related to the required congruence between the level of consumption of the flow at the level *n* and the supply of the flow per hour of work at the level *n-2* (the PS sector).

The same approach can be followed to perform a congruence check that goes a step further down, moving to the interface level *n*/level *n-3*. That is, considering the demand of exosomatic energy of the "whole society" and the actual supply of exosomatic energy achieved by the "Energy Sector" (ES). This implies adding two additional relations, which are indicated in Fig. 1: (i) Expected Power Level in the supply of exosomatic energy (EPL_{ES} = TET/HA_{ES})$_{demand}$ from the energy sector; has to be matched by (ii) Supply per Hour of Work in the energy sector (SHW_{ES} = TET/HA_{ES})$_{supply}$. There are different relations that can be used to explore the implications of this forced congruence, and they are illustrated in Fig. 15 when defining in redundant ways EPL_{ES} and SHW_{ES}. Here, we want to focus on a relation which is relevant for the determination of the quality of energy sources. In particular, we want to deal with the concept of EROI (Energy Return On the Investment). The EROI is the ratio between the quantity of energy delivered to society by an energy system and the quantity of energy used directly and indirectly in the delivery process. This index has been introduced and used in quantitative analysis by Cleveland et al. 1984; Hall et al. 1986; Cleveland, 1992; 2000; Gever et al. 1991. This value is important since it makes it possible to establish a relation between TET and ET_{ES} (TET = ET_{ES} x EROI). That is, it deals with the characterization of SOET+1 in the lower part of Fig. 8, and therefore it provides the non-equivalent representation of the constraints affecting the dynamic budget of societal metabolism, as seen from the "heart" side.



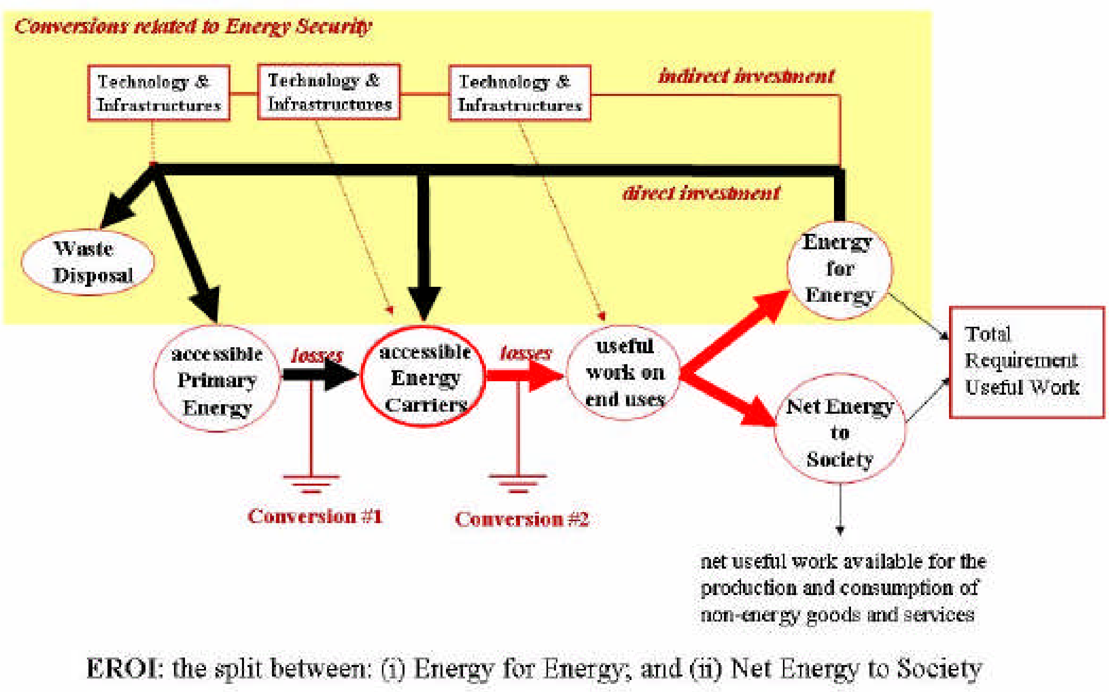


Figure 15. Different societal levels and the conversions to the energy sector.

When using this approach we can calculate the "expected" value of EROI by using the expression indicated in the box of Fig. 15. That is, we can plug in that expression typical benchmark values of a developed country (listed in the box of Fig. 15). In this way, we obtain an estimated value of EROI of about 13/1. This makes it possible to check the consistency of this value with the empirical values assessed for the current EROI of fossil energy by Cleveland (2000) and Hall and Klitgaard (2006). The empirical evidence provided by these studies confirms this indirect estimation.

This leads to our last consideration about the quality of fossil energy and more specifically the quality of oil as main source of energy carriers to society. As noted earlier, the dynamic budget of the exosomatic metabolism of a developed society must be based on a good Strength of the Exosomatic Hypercycle. This is an image suggested by Ulanowicz (1986) to explain the stability of dissipative networks in ecological systems. The relative concept is easy to understand. In order to be stable dissipative systems must have a part which is generating a net surplus of energy (the productive compartments), and a part which is purely dissipative (the final consumption compartment). Without a productive part, making available the energy input, the metabolism could not be sustained. Without the purely dissipative part the hypercycle out of check would simply blow out. Therefore, the stronger is the hypercycle, the larger must be the purely dissipative part. On the other hand this implies that a stronger hypercycle (generating more stress on the stability of boundary conditions) has to be associated with a larger investment of the resources consumed within such a system in adaptability (Giampietro, 2003 – Chapter 8).

Let's now apply this concept to MSIASEM analysis using the two graphs of Fig. 16. The upper part shows the hypercycle (to which the acronym SEH refers) which has to match the value determined by the Bio-Economic Pressure. This representation is based on the scheme already used in Fig. 8 *of the first paper of this series*. That is, this hypercycle is calculated at the level of the PS sector. This means that the assessment of a Net Supply per hour of work does not deal only with the supply of energy carriers, but also with the production of exosomatic devices and other technical infrastructures used by society. This explains why the two checks referring to the PS sector and the ES sector illustrated in Fig. 5b are different. The graph shown in the lower part of Fig. 16 is useful to discuss the nature of this difference. Within the energy flows determining the pattern of exosomatic metabolism of a developed country, there is an internal loop of exosomatic energy, which is established using different energy forms. In fact, when studying the exosomatic metabolism of society it is crucial to make a distinction between: (i) primary energy sources – e.g. oil fields, coal mines; (ii) energy carriers – e.g. fuels and electricity; and (iii) final energy services (the task achieved with end uses of energy).

Another crucial distinction is between: (1) direct energy investments (final energy end uses invested in the loop); and (2) indirect energy investments (final energy end uses invested in making exosomatic devices and infrastructures required for the loop). This makes the relative accounting of EROI problematic, since over an autocatalytic loop it is impossible to define a "substantive" quantitative assessment, expressed in linear output/input (Giampietro and Mayumi, 2004; Giampietro, 2006). Again, the combined effect of ILA and Mosaic Effect on multiple levels, can be used to get out from this impasse by providing two non-equivalent systems of accounting for the EROI: (1) one which is related to the characterization of BEP ←→ SEH (when including the direct and indirect inputs) and (2) one related to the characterization of EPL_{ES} ←→ WHW_{ES} (when considering only the balance of energy carriers). Each of these two characterizations implies arbitrary decisions of the analyst about the system of accounting, but the combination of the two increases dramatically the robustness of such an analysis.

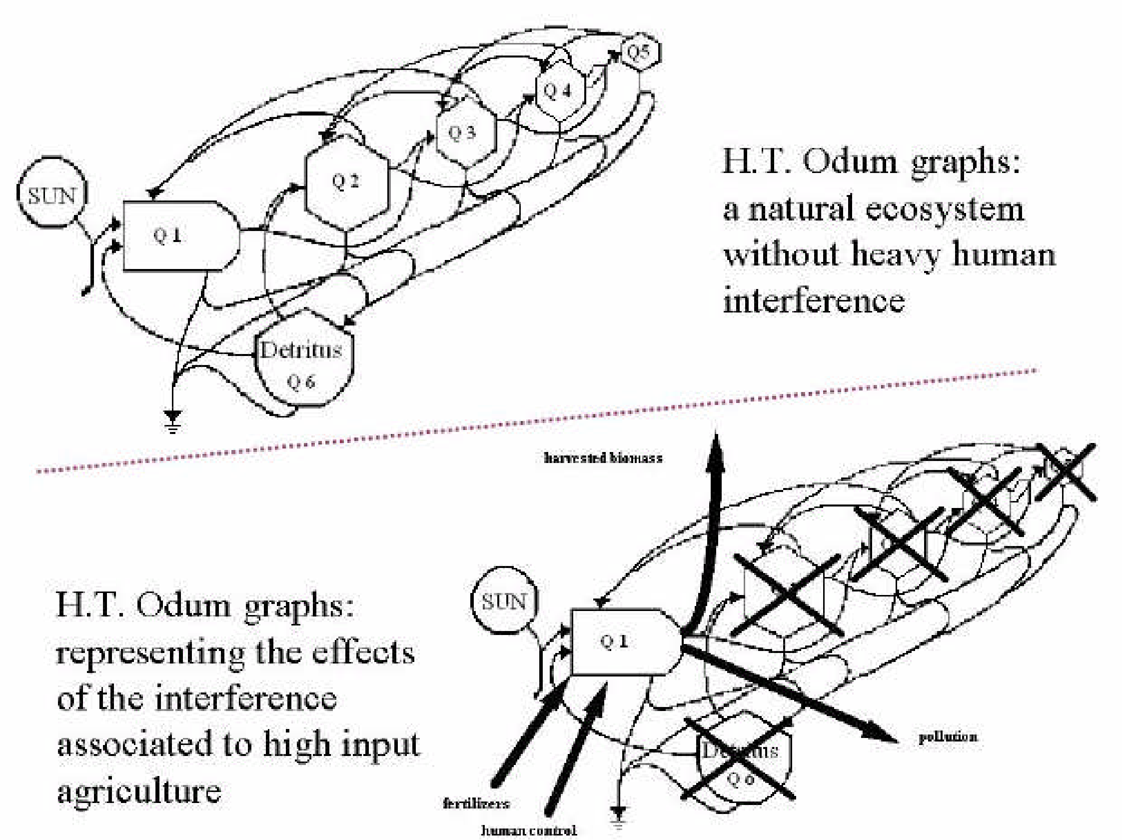


Figure 16. The energy flows that determine pattern of exosomatic metabolism of a developed country.

Just to clarify how serious the addiction to oil of developed societies is, one has to consider that the total energy consumption of a society depends on its aggregate requirement of useful work (on the right of the graph) which can be split between:
(1) Net Energy to Society – used for the production and consumption of non-energy good and services; and (2) Energy for Energy – used for the internal investment within the energy sector needed to deliver this useful work. This scheme indicates clearly the tremendous advantage of fossil energy over alternative energy sources. In relation to the costs of production, oil has not to be produced, it is already there. Moreover, in the previous century it was pretty easy to get: the EROI was 100 MJ per MJ invested in finding and extracting it! (Cleveland et al. 1984). The conversion of oil into energy carriers (e.g. gasoline) and their distribution implies only a minor additional cost. Finally, due to the high concentration of the energy flows in oil fields and coal mines both the cost for waste disposal and land demand interfering with ecological processes, was not considered a major issue, until acid rain deposition and global warming forced world economies to consider the idea of internalizing these costs. Still, so far, the major burden of the waste disposal of fossil energy has been paid by the environment, without major slash-back on human economies. Compare this situation with that of a nuclear energy in which uranium has to be mined, enriched in high tech plants, converted into electricity in a different but also high tech plants, waste have to be processed and then kept away (for millennia!) both from the hands of terrorists and from ecological

processes. The problem with the internal loop of biofuels has already be discussed in the first paper of the series. Hydrogen is an energy carrier and not a primary energy source. Finally, photovoltaic power, when looking at the life cycle assessment of the production of the cells, also is far from the high quality of oil.

4. The interference of societal metabolism with ecosystem metabolism

4.1 A brief history of the concept of metabolism and dissipative systems

The "metabolism of human society" is a notion used to characterize the biophysical processes occurring within a society that are necessary for its continued existence. This idea was presented beginning in the mid-19th century by authors such as Marx, Liebig, Boussingault, Moleschott, Arrhenius, Podolinski (for an overview see Martinez-Alier, 1987; Fischer-Kowalski, 1997). Parallel to the development of the concept of societal metabolism in the social sciences, several ecologists worked on the concept of ecosystem metabolism. In this field, E.P. Odum (1953 – third edition in 1971), Margalef (1968), H.T. Odum (1971; 1983; 1996), Ulanowicz, (1986); Holling, (1995). That is, several authors have pointed at the existence of 'systemic properties' of ecosystems that are useful in studying and formalizing the effect of changes induced in these systems. As observed for the concept of societal metabolism, the concept of ecological metabolism of ecosystems entails the existence of expected patterns of ecosystem properties over the relative size of functional compartments, expected patterns of energy and matter flows per unit of land, relative values of turn-over times of components, and the structure of linkages in the structure of networks and graphs used to represent ecosystems.

According to H.T. Odum, the global work of nature and society results in interconnected webs of energy flows and energy transformations that give rise to hierarchical energy patterns across different levels and scales (Odum, 1988, 1996). Within this perspective we can imagine that this chain of relationships can be used to define a scale for the biosphere in relation to the other self-organizing processes operating within it - this is what Odum called "emergy synthesis" (Giampietro and Ulgiati, 2005). According to this narrative there is a metabolism of Gaia, resulting from the metabolism of different typologies of ecosystems, within which human economies are embedded. Recent developments of these ideas within the emerging field of complex system theory led to the design of concepts such as *ecosystem integrity* (Ulanowicz, 1995) and *ecosystem health* (Kay and Regier, 2000). Methodological tools to evaluate the effect of human-induced changes on the stability of these ecological processes focus on structural and functional changes of ecosystems (Ulanowicz, 1986, 1997). In this regard, the concept of metabolism is crucial since it provides:

(i) expected types over the relative size of functional compartments;

(ii) expected values of energy and matter flows per unit of land;

(iii) expected values of turn-over times of components, and

(iv) typologies of linkages in the structure of networks and graphs used to represent ecosystems.

These types and benchmarks can be used to study the effects of the interference associated with human activities (with the competing establishment of patterns associated with the metabolism of socio-economic systems).

Finally, it is time to go back to the metaphor of a Yin-Yang tension over human use of material and energy flows over cycles versus linear flows (discussed in the first paper of this series). We can say that when the cycles of nutrients in the agro-ecosystems are closed, there is a high compatibility between the set of activities performed by the humans and the set of interactions found in the community operating in the ecosystem. That is, humans are expressing locally actions (exactly like a carnivore eating a prey), which on the large scale are not altering the definitions of species (structural types) and relative niches (functional types), which are associated with the typology of ecosystems in which they are operating. On the negative side, this implies that the flow of biomass appropriated by humans inside the ecological processes must remain into the limits determined by the characteristics of the particular metabolism of the exploited ecosystem. This is ecologically benign, since humans, with their pattern of production and consumption, are within the limits provided to them by the ecosystem which embodies their activity. In this situation, a human society is evolving inside the ecosystem, in the sense that it is sharing same of the metabolic flows and respecting the constraints of congruence over the relative flows (e.g. the long rotation time in shifting cultivation performed under low demographic pressure in pre-industrial societies). This, solution, however, can imply the inability to compete against other social societies, which taking advantage of stocks and disregarding long term compatibility with the environment, are capable of expressing a large variety of behavior and more applied power.

The other view of a metabolism based on a large flow of inputs is associated with a situation in which the pace of societal metabolism requires a power level (per hour of labor) and a power density (per hectare) in the production of flows (throughput) which is no longer compatible with natural patterns occurring in the ecosystems. For example, in agriculture, this can imply that the resulting density in supply of food per hectare in the category of land use “crop production” becomes no longer compatible with the natural distribution of ecological populations belonging to the different species associated with the given typology of ecosystem. Because of this, humans must replace the mechanism of regulation of the distribution of biomass over different species. That is, they must become, through colonization, totalitarian rulers of the system. Obviously, this may be lethal for biodiversity, through the total destruction of natural habitats. However, when looking at these changes adopting a short term, human perspective, these changes make it possible to produce food at the intensity required by the Bio-Economic Pressure (Expected Power Level per hour of work) and Demographic Pressure (Expected Power Density per hectare of colonized land in the agricultural sector).

When looking at the metabolism of ecosystems and at the metabolism of societies we have to acknowledge that the logic, the controls, the optimizing goals, and the technical coefficients found in the two systems (e.g. high tech human societies *versus* terrestrial ecosystems) are clearly different. Actually, we can define the pattern of production in high input agriculture as a clear example of the struggle of two different forms of metabolism competing over the same set resources (water, land, nutrients). Humans are literally kicking out the controls and the processes expressed by terrestrial ecosystems from the areas of land they colonize. Fossil energy (which made possible the industrial revolution), for the moment, is providing a clear edge, at the local scale, to humans in such a struggle. The nature of this competition deserves the maximum attention. In fact, at the large scale, humans are still fully dependent on the free services provided by ecosystems and Gaia. Therefore, the stabilization of the struggle of two logically independent forms of metabolism competing for the same resource requires the ability of learning about how to co-evolve across scales. That is, a sustainable solution has to be based on an integration of the different patterns of expected flows (expected from humans and expected from ecosystems), rather than the elimination of one of the two. This is especially important for humans, since, if the second solution will be enforced, in the long term and at the large scale, it is the flow of exosomatic energy controlled by humans that will be dramatically reduced!

The concept of linearization of nutrient cycles associated with the colonization of ecosystems can be discussed using Odum's metaphor of ecosystem metabolism. The work of the two Odum brothers is so famous that it does not require explanation. It is important to note, though, that their analysis implies the hidden adoption of the assumptions about the ability of metabolic system to express an expected identity (patterns of structural organization). The representation of human colonization of ecosystems is shown in Fig. 17 (the same concept was discussed in the first paper using Fig. 5a). This means that ecological systems, according to this approach, can be considered a good example of metabolic systems organized across levels, for which it is possible to calculate a set of expected benchmark values (e.g. transformity ratios, relative size of compartments, EMergy flows per ha). That is, these metabolic systems can be associated to known and expected typologies. This assumption is crucial for making possible an analysis of level of interference generated by human intervention. According to this analysis, this approach provides a non-equivalent view of the process of intensification of agriculture, and a clear link to the dramatic reduction of bio-diversity associated with monoculture.

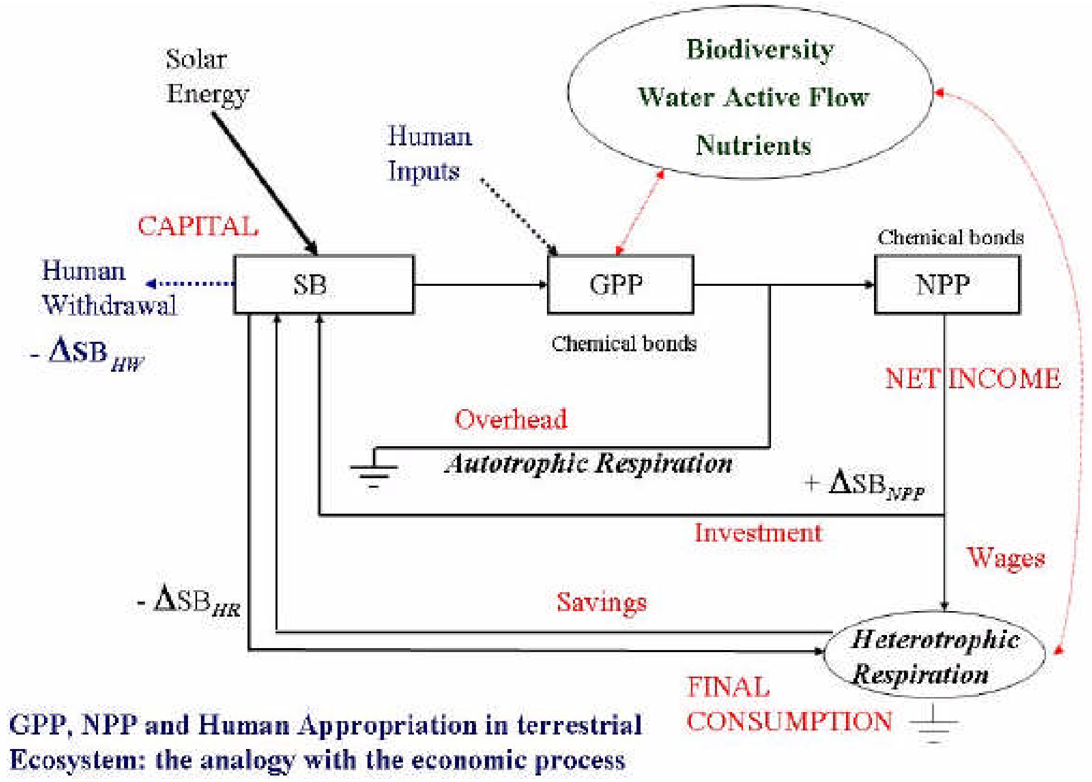


Figure 17. The human colonization of ecosystems using an ecological perspective.

After looking at a representation of the interference done by humans on ecosystems using an ecological perspective (Odum's view in Fig. 17), let us now use an economic perspective to represent human interference as a destruction, to a certain degree, of the original integrity of ecosystems. This view is given in Fig. 18. In this metaphor, the "economic process" of a given ecosystem starts with a given endowment of capital (the Standing Biomass, SB, at time zero). This capital generates a gross profit (the Gross Primary Productivity, GPP, measured in a flow of chemical bonds made available for further energy transactions) for the ecosystem, by taking advantage of solar energy and other inputs. Within this analytical frame we can define the autotrophic respiration as a sort of overhead that the plants impose on their supply of chemical bonds to the rest of the ecosystem. That is the gross profit for the system is reduced to pay such an overhead, and this defines the supply of Net Primary Productivity (NPP): the Net Disposable Income for the rest of the ecosystem (measured in chemical bonds). This Net Disposable Income can be divided between: (i) wages (food for heterotrophic respiration → boosting the activity of animals); and (ii) saving (increasing the amount of standing biomass). At the same time, the compartment of final consumption can balance local differences between final consumption and wages (in the two directions) either by saving the excess or by withdrawing from saving in case of shortages. The overall balance of this savings or withdrawal will determine whether or not the Standing Biomass will remain the same, be reduced or increased. The activity of the compartment of final consumption (heterotrophic respiration) is crucial for the generation of the Gross Primary Productivity in the first place. In fact, it is in charge for the recycling of nutrients and the preservation of biodiversity. Biodiversity is crucial for adaptation, which copes with the

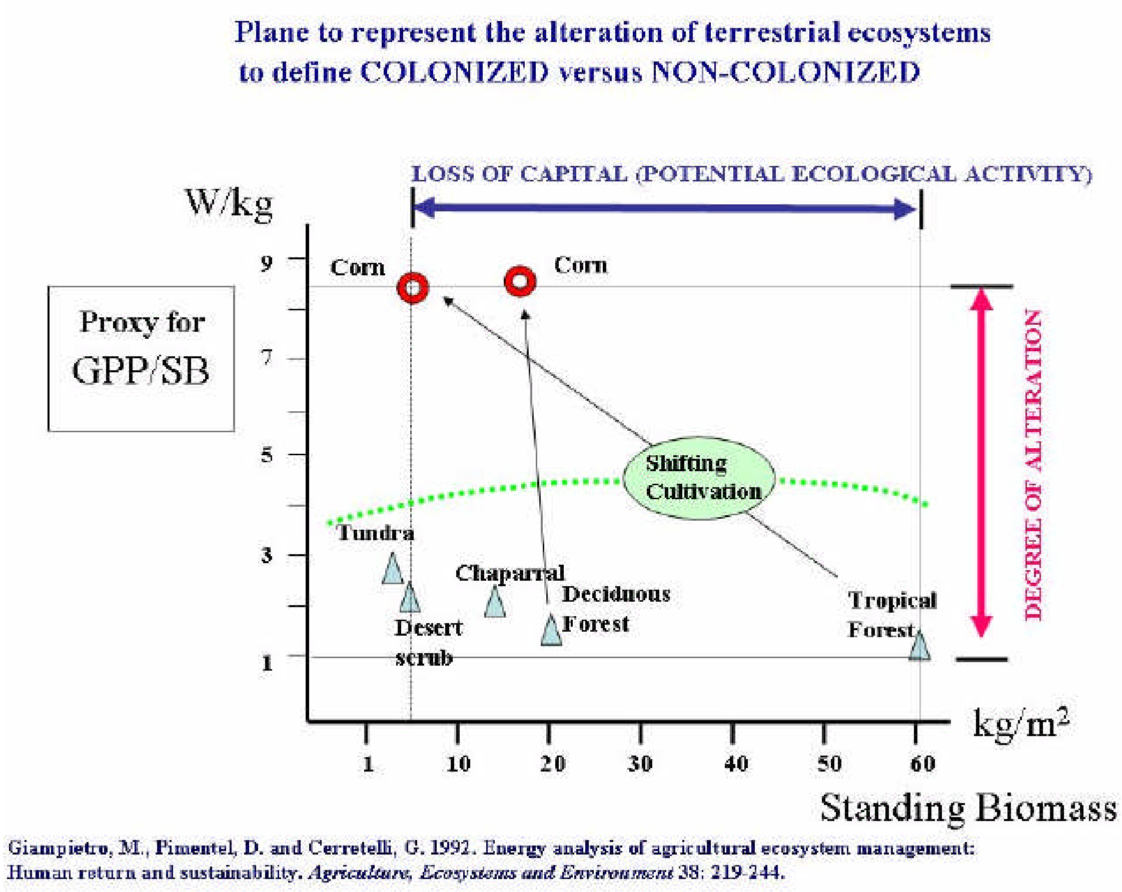


Figure 18 The human colonization of ecosystems using an economic perspective.

obsolescence of the capital. Therefore, as noted in the case of the metabolism of human societies, an ecosystem must operate by balancing its fixed and circulating investments over the different competing tasks of production (autotrophic standing biomass) and consumption (heterotrophic standing biomass). In order to produce more, more plants have to be eaten, the fixed investment has to be balanced with the circulating investment. This reminds us of the rationale suggested by Zipf about economies perceived as bio-social organisms . . .

Let us now see how the MSIASEM approach can be used to study the effect of human colonization of ecosystems in terms of an alteration of the integrity of their patterns of metabolism. With colonization humans are tampering with the mechanisms regulating the balance of investments among the different compartments operating at different levels. To apply the MSIASEM approach to this task, we have to change, in the analysis, the choice of the "fund resource" used for calculating the metabolic rates of relevant flows. That is, when discussing of the interface between societal and ecosystem metabolism we no longer map the flows of money, food, energy and matter (or letters) against a multilevel matrix of compartments defined using the fund resource "human activity." Rather we map these flows against the fund resource "land," by using a multilevel matrix of compartments defined using categories of land uses or land covers.

That is, when mapping the "power level" of money flows, endosomatic energy flows (food), exosomatic energy flows and other critical material flows (e.g. water, nitrogen) against the fund resource "human activity" we obtain a quantitative analysis, which deals with a socio-economic reading of the sustainability issue. On the contrary, when dealing with the human interference on ecosystem metabolism the "power density" of money flows, endosomatic energy flows (food), exosomatic energy flows and other critical material flows (e.g. water, nitrogen) has to be mapped against the fund resource "land." By doing so, it becomes evident that human colonization forces terrestrial ecosystems to operate in a totally unnatural configuration of their structural organization, since colonization implies altering the expected relation between: (i) the amount of standing biomass per hectare; (ii) the amount of Gross Primary Productivity generated per hectare; and (iii) the amount of nutrients recycled inside the system.

When mapping the intensity of the flows per unit of land, the concept of ecosystem metabolism implies for known typologies of ecosystems, a set of expected benchmark value for: (i) standing biomass per hectare; (ii) flows of matter and energy per hectares; and (iii) a given expected relation over these values. The existence of these "expected values" makes it possible to study the interference generated by human intervention. Colonization entails determining substantive changes over these expected values. In fact, the interference provided by humans has as goals: (1) to reduce as much as possible the ecological compartment in charge for final consumption; (2) to supply in massive terms technical inputs to boost the production of Gross Primary Productivity (and the consequent NPP); and (3) to export as much as possible the produced profit outside the system (harvested crops). The consequent linearization of flows is associated with the elimination of the role that final consumption plays in the natural pattern of closure of nutrient cycles. After a certain degree of alteration the strategy of linearization of flows becomes a must. In fact, below a certain threshold of standing biomass – e.g. the bare soil in monocultural cropping systems – what is left of the original terrestrial ecosystem has a very limited ability to recycle nutrients, using the original portfolio of natural interactions based on the biodiversity left in the existing biomass.

When using the economic metaphor described in Fig. 18 we can recognize, in the human attitude toward terrestrial ecosystems, the typical behavior of colonizing countries over the economy of a colonized economies. The economy is organized in order to export as much as possible what is produced. This implies that internal consumption is depressed as much as possible, whereas heavy investments in the colonized economy are performed, only in the primary sectors, in order to be able to extract as much as possible valuable flows out of the colonized system. The definition of "value" for the produced flows, however, reflects the characteristics of the metabolism of the colonizing system and not of the colonized one. The insight provided by Fig. 5, Fig. 17 and Fig. 18 can be used to characterize and represent the degree of alteration of the original pattern of metabolism of terrestrial ecosystems (e.g. categories of natural land covers) when they are replaced by human controlled categories of land uses. In this way, it becomes possible to define a set of benchmarks, which can be used to characterize in quantitative terms what should be considered as "colonized land" versus what is not colonized land.

This type of analysis was originally developed (Giampietro et al. 1992) according to a thermodynamic reasoning to characterize levels of alteration of terrestrial ecosystems.

Let us first define the plane which is used for such a characterization: (i) the horizontal axis measures standing biomass per unit of area (e.g. kg/m^2); and (ii) the vertical axis measures the amount of water associated with the photosynthesis linked to Gross Primary Productivity. This selection of variables is required to be able to use a narrative associated with the field of non-equilibrium thermodynamics (= improbability is linked to a very high level of entropy disposal per unit of biomass). However, for those readers that are not obsessed by using a very hard science analytical approach, any proxy of the ratio GPP/SB will do it. The simple version of these thermodynamic principles is that there is an expected value for the ratio GPP/SB which can be considered as "natural" and can be associated with a typology of terrestrial ecosystems. Ratios GPP/SB which are associated with categories of agricultural land uses tend to be "different" from (actually "much higher than") the expected natural values. The larger the differences in the value of the ratios characterizing the original ecosystem type and the category of land use that replaced it, the more intense the alteration induced by humans.

Reflecting this rationale, different typologies of natural terrestrial ecosystems are indicated by the triangles on the plane. These values represent specific benchmarks for different typologies of terrestrial ecosystems. The same applies to the characterization of agronomic land use categories (indicated by circles). The rationale of this analysis is justified by the existence of a set of internal relations illustrated in Fig. 17 and Fig. 18. Again, some agronomic categories of land use may imply boosting the rate of Net Primary Productivity (which can reach levels typical of a tropical forest) even though the average value of Standing Biomass on the fields (averaged over a year) is much lower. Crop systems, especially those based on monoculture can generate a lot of biomass per hectare at the moment of the harvest, but for the rest of the year hold very little biomass in place. As a result the value of SB (in kg per area) averaged over a year is pretty low. When considering the ratio between GPP and SB we can detect a lack of integrity in the terrestrial ecosystem or a very unlikely situation for agro-ecological system, whenever we find a high value for this ratio (a large value for NPP coupled to a very low value of SB). For example, in monocultures this value is several times higher than the natural benchmark expected for the terrestrial ecosystem that was replaced.

More direct would be the thermodynamic explanation of the indication given by this graph. Very high levels of entropy disposal per unit of biomass (W/kg spent on transpiration of water during photosynthesis) indicate an improbable state for biological systems that if let undisturbed would tend to minimize the entropy dissipation per unit of biomass (and stocking in this way more biomass per hectare) – for more on this Giampietro et al. 1992.

This method of representation of the characteristics of the metabolism of natural ecosystems and categories of colonized land is very important for several reasons:

(1) it establishes a criterion of discussion on how to define what should be considered as Colonized land versus Non-Colonized land;

(2) it makes it possible to use benchmark values for typologies of ecosystems and for typologies of colonized land associated with crop production (with Land Use categories) and therefore characterize levels of stress, when looking for critical thresholds;

(3) it can be used also for characterizing the density of flows in consumption for social systems - e.g. when characterizing categories of land use in the household sector (residential, urban versus rural, compact cities versus urban sprawl);

(4) it makes it possible to have a skeleton of benchmarks/indicators within the MSIASEM approach that can be used to establish local bridges with other indicators of environmental impact to be adopted in different situations and in different socio-economic and ecological contexts;

(5) it makes it possible to check the existence of biophysical constraints on the supply of flows that are associated with large land requirement (see the example of the analysis of the power density for biofuel supply discussed in the first paper of this series);

(6) it makes it possible to establish a bridge across different systems of indicators of stress and environmental impact across hierarchical levels of colonization of land. That is, the effect of such an alteration can be studied, in a non-equivalent way, by using other more specific indicators of environmental impact (e.g. bio-indicators at different scales, fractal dimension of the cropping systems, load of nitrogen in the soil). That is, the parallel mapping of the same flows (money, food, energy, key material flows) against a multi-level matrix of “human activity” and “land covers/land uses” makes it possible to handle, in an integrated way, the analysis of changes characterized by the various sets of indicators on both the socio-economic and the ecological side;

This bridge is important since humans should learn as soon as possible how to integrate the metabolism of their societies with the metabolism of ecosystems rather than increasing the already high level of disturbance. The problem with this integration is represented by the fact, that ecosystems have their own strategy on how to produce and consume biomass for stabilizing their own metabolism. The fact that humans’ agenda and ecosystems’ agenda about how to express their own metabolism do not coincide, generates a competition between human societies and ecosystems over land. The effect of this competition can be studied by looking at: (1) the relative area controlled by the two types of metabolism - the overall ratio “colonized”/“non-colonized land”; and (2) the level of disturbance associated with the specific categories of land use within the “colonized land.”

When looking at the issue of biofuels from this perspective, we can say that if the idea is to use biofuels as "the silver bullet" for both: (i) substituting oil; and (ii) eliminating GHG emission, then this solution is a lemon. They imply too much Yin (ecological compatibility by closing the carbon cycle) but too little Yang (incompatibility with actual socio-economic functions). If the idea is to use biofuels by keeping the actual pattern of exosomatic metabolism (at the actual value of Yang, that is at current values of BEP) then a massive move toward biofuel will be a disaster for the Yin perspective. That is, if biofuels will be implemented "no matter what" to replace oil, it is very likely that this choice would imply a skyrocketing in: (1) the overall ratio "colonized"/"non-colonized land"; and (2) the amount of land in the category of land use "cropping" (either plants or trees) within the compartment of "colonized land." These changes will be very problematic for the stability of the metabolism of terrestrial ecosystems, especially for the preservation of natural habitats.

Biomass is a crucial piece of the puzzle of human co-evolution with ecological processes on this planet. Therefore, it would be wise to look at biomass as a key element of sustainability in relation to its multifunctional purposes rather than focusing only on the use of biomass for producing fuels.

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