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Assessing the quality of alternative energy sources: Energy Return On the Investment (EROI), the Metabolic Pattern of Societies and Energy Statistics

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ABSTRACT

This paper presents an initial challenge to tackle the every so "tricky" points encountered when dealing with energy accounting, and thereafter illustrates how such a system of accounting can be used when assessing for the metabolic changes in societies. The paper is divided in four main sections. The first three, present a general discussion on the main issues encountered when conducting energy analyses. The last section, subsequently, combines this heuristic approach to the actual formalization of it, in quantitative terms, for the analysis of possible energy scenarios. Section one covers the broader issue of how to account for the relevant categories used when accounting for Joules of energy; emphasizing on the clear distinction between Primary Energy Sources (PES) (which are the physical exploited entities that are used to derive useable energy forms (energy carriers)) and Energy Carriers (EC) (the actual useful energy that is transmitted for the appropriate end uses within a society). Section two sheds light on the concept of Energy Return on Investment (EROI). Here, it is emphasized that, there must already be a certain amount of energy carriers available to be able to extract/exploit Primary Energy Sources to thereafter generate a net supply of energy carriers. It is pointed out that this current trend of intense energy supply has only been possible to the great use and dependence on fossil energy. Section three follows up on the discussion of EROI, indicating that a single numeric indicator such as an output/input ratio is not sufficient in assessing for the performance of energetic systems. Rather an integrated approach that incorporates (i) how big the net supply of Joules of EC can be, given an amount of extracted PES (the external constraints); (ii) how much EC needs to be invested to extract an amount of PES; and (iii) the power level that it takes for both processes to succeed, is underlined. Section four, ultimately, puts the theoretical concepts at play, assessing for how the metabolic performances of societies can be accounted for within this analytical framework.

Keywords: Energy Return On Investment (EROI), Energy Accounting, Energy Statistics, Social Metabolism, Metabolic Patterns of Societies, Energy Metabolism, Energy Analysis, Primary Energy Sources, Energy Carriers

1. Introduction

Energetics can be defined as the scientific discipline studying the relation between: (a) the set of structures and functions expressed by socio-economic systems; and (b) the set of energy transformations required to express them (Giampietro and Mayumi, 2009). Energetics has a long history (Carnot, 1824; Cipolla, 1965; Cottrell, 1955; Lotka, 1922; Jevons, 1865; Odum and Pinkerton, 1955; Ostwald, 1907; 1911; Podolinsky, 1883; Soddy, 1926; Vernasdky, 1926; White, 1943; 1949; Zipf, 1941), and it got a flash of popularity in the 70s, because of the first oil crisis. In that decade, Energetics was included in many academic programs and gained high visibility on the most popular scientific magazines (Georgescu-Roegen, 1971; 1975; Gilliland, 1978; Herendeen and Bullard 1976; IFIAS, 1974; Leach, 1976; Odum E.P. 1971; Odum H.T. 1971, Pimentel and Pimentel, 1979; Rappaport, 1968; 1971; Slesser, 1978; Steinhart and Steinhart, 1974).

Because of the natural inertia of the field, Energetics has kept producing a remarkable amount of work through the 80s, 90s and still today (Adams, 1988; Ayres and Warr 2005; Ayres et al. 2003; Cleveland, 1999; Cleveland et al. 1984; 2000; Costanza, 1980; 1981; Debeir et al. 1991; Fischer-Kowalski and Haberl, 2007; Gever et al. 1991; Giampietro and Mayumi, 2004; 2009; Hall et al. 1986; 2009; Hannon, 1981; 1982; Herendeen 1981; 1998; Kaufmann, 1992; Mayumi, 2001; Mayumi and Giampietro, 2004; Odum H.T. 1983; 1996; Patzek, 2004; Pimentel et al. 2007; Schnitzer and Ulgiati, 2008; Slesser and King, 2003; Smil, 1983; 1988; 1991; 2001; 2003; 2008; Stout, 1991; 1992; Tsuchida and Murota, 1987; Ulgiati et al. 1998; 2001; 2003; Watt, 1989; 1991).

However, two linked events: (i) the ample and cheap fossil energy supply in the 80s and 90s; and (ii) the acceptance of the dubious belief that human ingenuity will always find substitute for whatever limiting resources – including energy (= the takeover of "cornucopians" in the sustainability debate); resulted in the almost total disappearance of this scientific discipline from both academic program and popular scientific magazine in the 90s.

In the first decade of the third millennium, two other linked events: (i) climate change, and (ii) peak oil; are putting back, on the front burner, the set of forgotten questions, which used to be tackled by energetics: "Is it possible to move to a low carbon society and how?" "Can we define the quality of primary energy sources and how?" "Can we check whether a proposed alternative energetic pattern is both feasible and desirable for modern societies?" This last question is crucial in order to detect "hoaxes" in the search for alternative energy sources, which can imply wasting valuable resources and time in cul-de-sac research lines. In this paper we claim, that these questions can only be answered by getting back to the basic concepts and discussions proposed by energetics.

For this reason, we start this paper by presenting a few basic concepts of energetics, which have been known for decades, but which seem to have been forgotten in the recent debate over alternative energy scenarios. In particular we focus on the theoretical concept of Energy Return On the Investment (EROI) and its possible implementation in order to get a better informed discussion over possible energy futures. Then, we use these basic concepts to generate a useful characterization of the energetic metabolic patterns of modern societies. This characterization is based on an innovative interpretation of the fund-flow model proposed by Georgescu-Roegen.

The paper is divided in 4 sections. The first three sections illustrate three "tricky" points which often muddle the discussions within energetics:

Section 1 – Point #1: energy is a slippery concept for quantification, which requires a pre-analytical definition of the categories used for the relative accounting. Different energy forms – e.g. Joules of Primary Energy Sources (PES) associated with the kinetic energy of a waterfall and Joules of Energy Carriers (EC) associated with the kWh of electricity generated in hydroelectric plant – are of a different quality. This difference has to be addressed before handling the relative measurement and summing within a general accounting scheme. In the same way the amount of Joules of EC consumed in a task – e.g. the energy contained in gasoline - do not map directly onto the amount of useful energy associated with the corresponding End Uses (EU) – the km-person of displacement of drivers – the efficiency of the car or the wisdom of the driver may determine a different mileage for the same amount of gasoline;

Section 2 - Point #2: the analysis of the process of exploitation of primary energy sources deals with a chicken-egg process: you must have and invest a certain amount of energy carriers in the exploitation of a primary energy source in order to generate a net supply of energy carriers . . . This forced circularity in the transformation of energy flows, associated with the exploitation of PES, implies a non-linearity in the expected relations over input and output flows. This fact is often missed by those that adopt reductionist approaches (i.e. that of linear input/output accounting);

Section 3 - Point #3: the implementation of the concept of Energy Return On the Investment cannot be obtained by using a simple number (e.g. an output/input ratio). Rather it requires an integrated set of information: (i) how big is the net supply of Joules of EC that can be derived by the exploitation of a given PES – *checking external constraints*; (ii) how big is the investment which is required from the energy sector (in terms of capital, labor and an input of Joules of EC) to exploit a given PES – *checking the internal constraints*; (iii) the power level of both the investment and the returned flows – this entails acknowledging the relevance of the time dimension – that is, acknowledging the well known fact that ***energy is different from power***. We claim that a metabolic pattern entails the existence of a profile of power levels characteristics of the different compartments making up the socio-economic system, which determine the relative size of the various compartments making up a society;

Section 4 - The last section combines these concepts into a heuristic approach that can be used to deal in quantitative terms with the analysis of energy scenarios. It introduces the concept of the "metabolic pattern" of modern societies in which the expected relations among structures/functions and the required energy transformations associated with these structures/functions are expressed using a general and useful analytical framework (a meta-grammar in technical jargon). A section of conclusions gives a wrap-up of the discussion.

Section 1. The conceptual distinction between different energy forms

No economist would accept an accounting done by summing together: 100 US dollars, 100 Euros and 100 Chinese Yuan, into an overall sum of 300 "monetary units". The category "monetary units" does not carry any useful economic meaning. An economist would require that in order to properly sum these different amounts of money one has to: (i) select a currency of reference; and (ii) transform the numerical value of the various addends into an equivalent amount, expressed in the reference currency, by using appropriate conversion factors (keeping in mind that it changes over time); and

(iii) summing up the various addends only when they are expressed in the same currency for the same year.

The same situation is found in energetics, in which one has to follow the same approach when summing energy forms of different quality. For example, the production of 1 joule of **electricity** (a particular type of EC) requires spending a certain amount of joules of **fossil energy** (whose assessment must refer to a particular type of PES). The overall conversion ratio – e.g. Joules of fossil energy/Joules of electricity - depends on: (i) the type of Primary Energy Source used – e.g. oil, coal, natural gas; and (ii) the quality of the technology used – e.g. more efficient large plants versus less efficient small generators. For example, the ratio of conversion Joules of fossil energy/joules of electricity used to be 3/1 (as average for whole countries) in the past and it is moving down to 2.6/1 in these days BP statistics - BP (Conversion Factors) account for an average conversion rate of 2.67 referring to modern power stations. Other sources consider this conversion factor for Europe to be around 2.5 (De Keulenaer and Grawe, 2006). The general consensus is that this value is on the decline due to overall technical improvements. Therefore, in analogy with the conversion factors among currencies, we find that the "exchange rate" between Joules of PES and Joules of electricity *does* change in time.

According to this rationale, if we want to sum 100 Joules of electricity to 100 Joules of gasoline to calculate the overall consumption of a country, we should apply a "conversion factor", required to make it possible to compare and sum these two non-equivalent amounts of Joules of EC referring to different energy forms. That is, we have to express the MJ of two different Energy Carriers (electricity and gasoline) in an equivalent amount of a PES (a reference standard) and then sum them. In this case, the 100 Joules of electricity have to be accounted as 300 or 260 Joules of "primary energy equivalent" (usually expressed in "oil equivalent" - as oil has been the dominant fuel of our contemporary way of accounting) in line with the conversion factors stated above. The current ignorance of the available knowledge of energetic principles is well illustrated by the fact that recently, the OECD, Eurostat and IEA adopted a protocol (OECD; IEA, Eurostat, Energy Statistics Manual, 2004) for their energy statistics that, after having introduced a new category for energy accounting – a category labeled "energy commodities" - is actually summing Joules of hydroelectricity to Joules of oil. According to the principles of energetics the category "energy commodities" should be considered as the semantic equivalent of the category "monetary units" used for summing different currencies without considering exchange rate! Within this protocol, "primary commodities" (Joules of PES) are summed to "secondary commodities" (Joules of EC) following unclear and arbitrary transformation rules.

Concluding this discussion we can say that according to the theoretical concepts developed within energetics it is essential to make the following distinction between:

(i) ***Primary Energy Sources*** (PES) – they are physical gradients – e.g. solar energy, fossil energy stocks, waterfalls - making possible the generation of a net supply of Energy Carriers;

(ii) ***Energy Carriers*** (EC) – this category includes energy vectors – e.g. liquid fuels, electricity, steam - ***which are produced starting from a PES*** (or at times to produce more energy carriers from already existing energy carriers such as producing electricity from fuel) ***by consuming energy carriers to conduct this conversion phase***. Energy carriers are required by the various compartments of the society to perform a task. This includes the Energy Sector which must consume energy carriers to produce a net supply of energy carriers. It is important to note that energy carriers ***are specific for converters***

– e.g. hay is an energy carrier for mules, electricity is an energy carrier for vacuum cleaners, fuels are energy carriers for cars. This entails that energy carriers are usually not fully substitutable for each other – e.g. commercial airplanes cannot fly on electricity or hay;

(iii) ***End Uses (EU)*** – this semantic label refers to any type of useful work associated with the successful accomplishment of the tasks required by societal structures and functions – e.g. energy services delivered in the various sectors of the society (household, service sector, agriculture, etc.).

For historical reasons, out of these three available categories to refer to "energy forms", Primary Energy Sources were chosen as the reference "energy form" to be used for energy accounting. This choice implies that the total consumption of energy of a given society used to be calculated in terms of "total requirement of a given PES". This has made possible to account for the amount of imported or exported PES such as Crude Oil, Natural gas. Since this accounting system was developed in the era of fossil energy, physical quantities of fossil PES – e.g. tons of oil or tons of coal - were chosen as the standard accounting rod for primary energy sources. Within this rationale, the embodied amount of primary energy source required for producing a joule of Energy Carrier was used as a sort of conversion factor to measure the overall amount of energy consumed by an economy in terms of PES.

It is important to note that the quantitative accounting of the particular PES used as standard for the overall consumption is **a physical amount** expressed using a physical quantity – e.g. barrels of oil, tons of coal, etc. - and not in energy units (Joules)! Those readers who had some training in energy analysis remember the use of Tons of Oil Equivalent (or even Tons of Coal Equivalent used in old fashion statistics) as the reference PES to express the total energy consumption of countries. This choice stresses the function of this assessment: assess the overall "biophysical demand" on the context that the energy consumption of a country entails (external constraints). That is, an assessment of total consumption expressed in Tons of Oil Equivalent indicates the size of the required stocks of PES or the required amount of imports which is associated with the expression of a given metabolic pattern.

Getting back to the example of the summing of Joules of electricity to Joules of coal, we have to note that electricity can be generated using different types of PES either fossil (oil, coal, natural gas) or renewable (waterfalls, wind, photovoltaic). These different processes of conversion do entail the definition of different "biophysical costs" of 1 Joule of electricity in relation to the adoption of different types of PES.

BOX 1 – General scheme of energy conversions within the society

* The accounting of ***primary energy sources***, by definition, must be done using physical variables such as barrels of oil, trillions of cubic meters of gas, tons of coal, tons of uranium. However, it is possible to assign to each one of these PESs a conversion factor which makes it possible to calculate an energy equivalent – e.g. Joules. However, one should be aware that this is a source of trouble.
* The accounting of ***energy carriers*** is done, in official statistics, using energy variables. The official SI unit for energy is Joule. However, different energy units are often used for different energy carriers: kWh for electricity; MJ for fuels – BTU and kcal are still used for heat.
* The accounting in quantitative terms of ***end uses*** is problematic if not impossible. There are situations in which it is possible to quantify energy services – e.g. tons-km of transported goods, lumen per square meter for illumination – however, when dealing with the complex set of activities performed in a modern society, and the crucial importance of qualitative factors in determining the value of the service– not all the tons-km are the same! - there are always qualitative factors impossible to quantify using energy units. For example, how to make a distinction between the physical work of a famous orchestra director and a policemen regulating the traffic?

That is, the *biophysical cost* of 1 Joule of electricity can be expressed in "kg of coal", or "liters of diesel", or "cubic meters of water falling through a certain height gradient". For this reason, in order to produce a standardized quantitative accounting system generating a set of comparable numbers (e.g. Joules of a given PES type) an additional rule had to be added. After defining the type of Primary Energy Source to be used as the reference standard – e.g. Tons of Oil Equivalent – it was necessary to define also an energetic equivalent of this type of PES. This implied moving from numbers referring to a given mass of chemical substances (tons) to Joules – e.g. 1 TOE = 41.85 Giga-Joules (10^9 J). This passage represents the first "trick" capable of bringing the required dose of ambiguity in the process of accounting. This ambiguity is required in order to sum apples and oranges - the energetic costs of 1 joule of electricity produced by waterfall summed to the energetic costs of 1 joule of electricity produced by burning coal. The application of this rule entails the claim that it is possible to convert a physical quantity referring to mass – e.g. Tons of something - into a numerical assessment of Joules of energy in a substantive way (= using a conversion factor which is accurate and valid regardless contexts and situations). Unfortunately this claim is not granted: (i) a ton of oil has different energy equivalents depending on the quality of the oil; and (ii) the category "calorific value" – the numerical equivalent in Joules of a ton of oil - does not map exactly onto other categories of energy forms (e.g. Joules of electricity or Joules of energy contained in gasoline). Not only there is a problem with a distinction to be made between high and low calorific values, but also the energetic usefulness of this numerical value always depends on the context – the same amount of heat can generate different amount of electricity when used in different processes.

Thus, we can say that this effort of standardization had the effect of reducing the accuracy of the quantitative representation and introduced confusion. This fact is especially evident when this approach is applied to the generation of electricity with non-fossil PES. For example, Joules of electricity (an Energy Carrier) produced by using nuclear power are often accounted as if they were a "virtual" quantity of Primary Energy Source consumed by the country. By adopting a common standard reference energy form – PES and TOE equivalent [1] - it becomes possible to compare the energy consumption of different countries, which are using different mixes of PES and EC.

However, this standardization introduces a lot of problems. These virtual TOEs do not emit CO_2, do not deplete oil reserve (positive features). On the other hand, they may imply other negative features - such as radioactive waste, or side effect of dams, or soil erosion - which are simply ignored when considering the generation of electricity with alternative sources as a virtual amount of Tons of Oil Equivalent. May be this is the reason why the new generation of energy analysts (those developing the protocols of Eurostat and IEA) decided to throw away the baby with the dirty water, when introducing the semantically challenging category of "energy commodities" in their protocols.

We have to admit that for a non-energy-expert the previous discussion can result pretty confusing. So to clarify the issue we provide, in this section, a general scheme explaining the basic accounting of energy conversions according to the principle of energetics, and a practical example of application of this scheme.

When framing the set of energy transformations taking place in a society in relation to these three energy forms, we have a series of two conversions in cascade:

Conversion #1 - PES → EC dealing with the external interface (context/black box) – this analysis is useful to check the external constraints (limits). Given: (i) the required mix of EC - electricity, fuels, heat – which has to be supplied; and (ii) the mix of PES - fossil energy and alternative energy sources – used to generate this supply; then it become possible to calculate the required amount of PES needed to guarantee the required consumption of EC.

Conversion #2 - EC → EU internal functioning of the society (black box/parts) – this analysis is useful to check the link between the pattern of energy transformations and the resulting expression of structures and functions within the society.

In this section we deal only with the first conversion – the generation of the required supply of Energy Carriers, which takes place within ***the energy sector*** of a society (an analysis of conversion #2 is given in the last section of this paper). In the analysis of Conversion #1 we find already a first serious problem that reductionism must face when attempting to quantify this set of energy transformations. As illustrated in **Fig. 1**, it is impossible to have a representation of the energy consumption of a society, even when considering only the energy sector, by using a single quantitative assessment – a single number of Joules.

[1] Commonly, there are two known forms of accounting for Hyrdo and Nuclear Energy in the Primary Energy Equivalent forms: 1) The Partial Substitution Method (or the Opportunity Cost Method) which gives electricity production from Hydro and Nuclear sources an energy value equal to the hypothetical amount of the fuel required to generate an identical amount of electricity in a thermal power station using combined fuels (usually an average efficiency of 38.5%); 2) The Physical Energy Content (the Present IEA Method) in which the heat from a nuclear reactor could be substituted by the heat obtainied by burning coal with efficiency of 33% and that conversions for hydroelectricity is values by is valued by the energy content of the electricity directly.

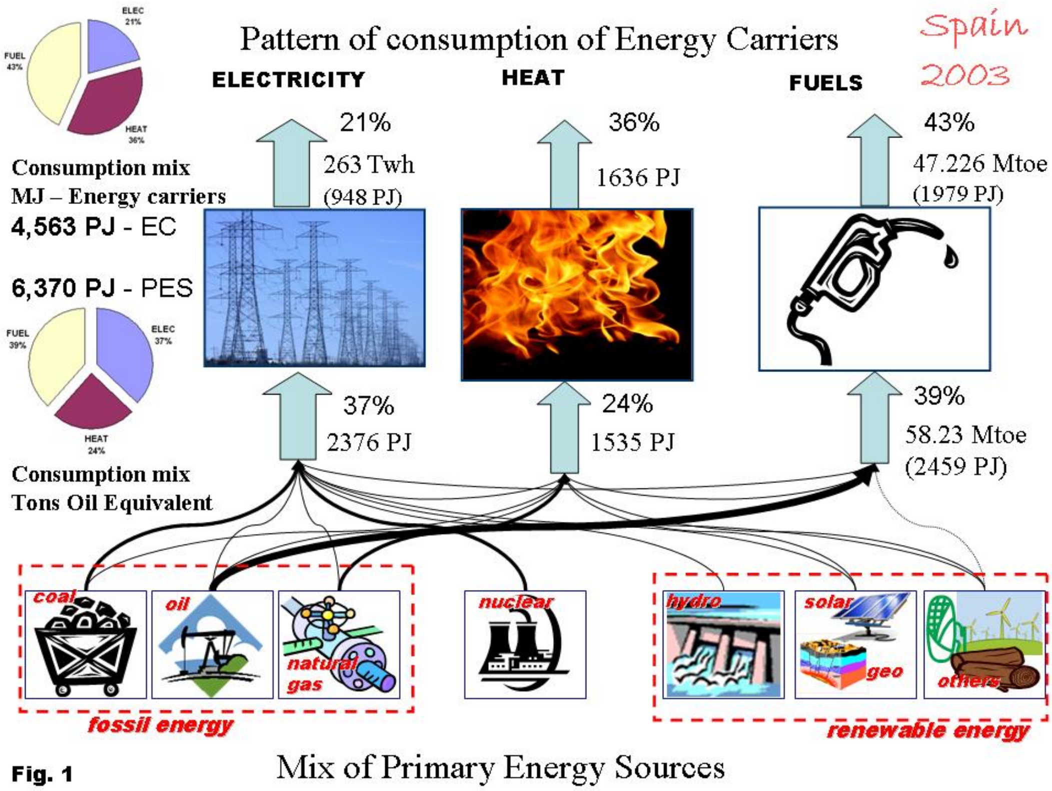


Fig. 1

The pattern of "*energy consumption*" in the energy sector of Spain, in 2003, is illustrated in Fig. 1. On the bottom we have the mix of "*energy consumption*" obtained by looking at numbers expressed in Joules equivalent of Primary Energy Sources - on the left side the PES derived from fossil energy, on the right side the PES which are considered as renewable, in the middle nuclear energy. On the top we have the mix of "*energy consumption*" when looking at numbers expressed in Joules of Energy Carriers (electricity, heat and fuels). It is easy to realize that if we want to adopt a quantitative characterization of this pattern of "*energy consumption*" using the category "energy commodities" - the one adopted by Eurostat - expressed in Joules, then we have to face a logical bifurcation in the quantitative analysis. In 2003 Spain consumed 37% of its "*energy*" in electricity (when calculating the assessment done using Joules belonging to the category PES), or only 21% of its "*energy*" in electricity (when calculating the assessment done using Joules belonging to the category EC).

That is, if we convert all the quantities of the graph in a common unit - Joules (or Joules of energy commodities as suggested by modern protocols of energy accounting) - then we should be able to handle the simultaneous presence of two non-equivalent assessments of total consumption:

* a total "energy" consumption of **6,370 PJ** when assessing this quantity in J of PES (Assuming that 1Mtoe = 41.868 PJ as the reference energy form and then by converting all the other PES sources into this equivalent ≈ 6,370 PJ);

* a total "energy" consumption of **4,563 PJ** when assessing this quantity in J of EC. (The conversions used for this assessment as; 1Kwh = 3.6 MJ for electricity; 1Mtoe = 41.868 PJ 1kcal for fuels and accounting for heat as Joules itself. Then the total

quantity in PJ of energy carriers is: electricity = 948 PJ; heat = 1,636 PJ; and fuel = 1,979 PJ. The sum of all carriers being 4,563 PJ)

The large difference between these two assessments (1,807 PJ of PES) can be easily explained by the losses of power generation, which depends on: (1) the particular mix of PES – for example the different profile of losses for the generation of 1 J of electricity in different processes such as nuclear or fossil fuels (the losses of this conversion can go from 3/1 to 2.5/1); the conversion losses from crude oil to produce gas/diesel oil, LPG and motor spirit for fuel as a carrier (the losses of this conversion can go from 1.3/1 to 1.1/1); and for obtaining heat from various other PES sources such as Natural or Derived Gas and other solid and liquid fuels (around 1.1 but may vary due to distribution); and (2) the particular mix of technologies used for the conversions; (3) the particular mix of EC - the aggregate requirement of electricity in the End Use, which implies a larger energetic cost of 1 Joule than heat or fuel in the conversion from Joules of PES to Joules of EC.

So this difference between Joules of PES and Joules of EC, in ultimate analysis, depends on an emergent property of the network of transformations taking place in the energy sector, and not on individual factors such as the quality of PES or the specific efficiency used in any of the conversions. This emergent property is highly likely to change with the different network systems varying for each county.

Section 2. the chicken-egg process of exploitation of primary energy sources

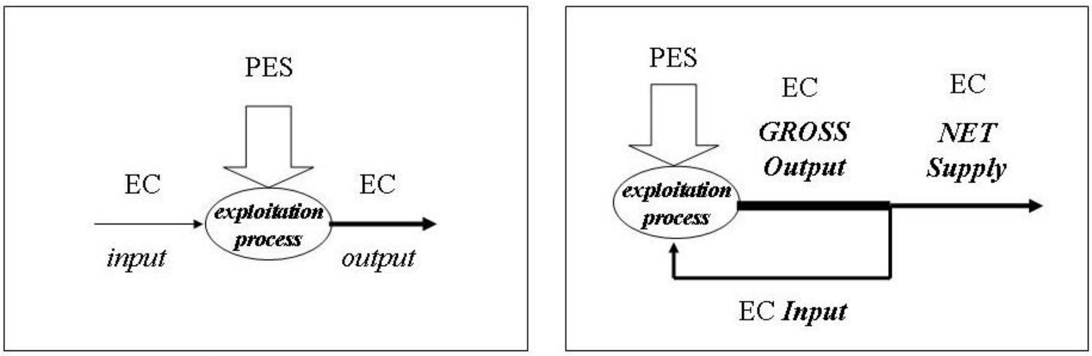
The impressive success of reductionism led to the widespread adoption of linear analysis of any process of production, which is generally represented using an input/output system of accounting. In this linear view, the efficiency of the process is captured by a simple number: the ratio between the output and the input flows. This approach is also applied to the analysis of the process of exploitation of PES. The mantra goes always as follows: "the higher the energy output per energy input, the higher the quality of the energy source". It should be noted, that the first law of thermodynamics prevents the possibility that in an energy transformation we can get an output larger than the input. As a matter of fact, the second law of thermodynamics makes the situation even worse: it is not even possible to break even. So it is obvious that when dealing with the analysis of energy transformations we should be more careful in defining the analytical setting and the labels assigned to the various numbers. As a matter of fact, it is only by adopting the distinction between PES and EC, which it becomes possible to get out from this thermodynamic impasse. When talking of an output/input larger than one, we must refer to the "return (Joules)" of energy carriers per "unit (Joules)" of energy carriers invested". That is, we are looking at only a part of the whole set of conversions, which are taking place in the process of exploitation. The losses of conversions plus the net output of the process of exploitation are paid by the amount of Primary Energy Source which is lost in the process.

Actually, in the 70s, the system of accounting developed under the name of "energy analysis" was developed around the concept of "Net Energy Analysis". This concept wanted to focus on the obvious fact, that it is not how much energy we find when exploiting a primary energy source which matters (available energy – e.g. solar energy getting on the crop fields), but the amount of energy that we can get out of the exploitation (accessible energy – e.g. the crops that we get after discounting the energy cost of cultivating and harvesting). However, a correct application of the concept of

Net Energy Analysis requires to add an additional complication to the system of accounting we must make **two distinctions** between: (i) Joules of **PES** and Joules of **EC** (as illustrated in Section 1); and (ii) **gross** and **net** production of Energy Carriers. This is the second tricky point dealt with in this section.

As observed by Georgescu-Roegen (1979) when looking at the energy literature of the 70s not all the authors were handling in the same way the accounting in relation to these two distinctions. In some analyses the distinction between "Gross and Net" were used to indicate the difference between the amount of PES consumed (defined as "Gross energy") and the amount of Energy Carriers made available to society (defined as "Net energy"). This distinction was focusing on the difference in the categories Joules of PES and Joules of EC. In other analyses the concept of net gain was used to point at the existence of primary energy sources of different qualities. In this second case the definition of Gross was the total output obtained in terms of energy carriers (Joules of EC), and Net was the net supply, determined as the gross supply of energy carriers minus the amount of energy carriers used as input (Joules of EC).

Again since for a non-energy-expert this discussion can appear confusing, we provide also in this case first a scheme clarifying the issue and then an example of application of this analytical framework to a practical case.



The linear view (simplification of reductionism)

The chicken-egg view (complexity of energetics)

Fig. 2

On the left graph of Fig. 2 we can see the conventional linear representation: the input (the investment) gets into the process of exploitation of PES and then an output comes out of this process (the return). As observed earlier, if the output is larger than the input, we are dealing with an accounting done in terms of Joules of EC, which is neglecting the amount of PES consumed in the process.

At times the neglecting of this information is not particularly relevant (e.g. the solar energy unused by the process of growing crops), other times this information is very relevant since a lower efficiency in utilizing the PES may imply worsening the situation in relation to external constraints (e.g. consuming oil at an excessive speed, generating too much CO_2, consuming more land or water per unit of net energy carrier delivered). So the two types of relevant information about this conversion are:

(i) the conversion of input into output of EC - relevant for internal purposes ("how much" input has to be invested by society in the exploitation – internal constraint);

(ii) the overall conversion "PES → net supply of EC" – relevant for assessing the external constraint to be faced (how much PES is needed for a unit of net supply of EC).

If we want to generate useful information in relation to this double task, there is a clear theoretical problem with the adoption of a linear representation. In the left graph of Fig. 2, we must assume that *the input of energy carriers* to be invested in the process is already available to the exploiter, *before the exploitation is* taking place. Therefore, when looking for a sustainable process of exploitation of a given PES, one has to assume, that it is possible to generate a quantity of Energy Carriers (a gross output) which is larger than the required (input), in order to be able to use a part of the output of energy carriers generated in the process, to cover the requirement of the input of energy carriers. This circular view of the process is illustrated in the right graph of Fig. 2. It should be noted that the direction of the arrows over this graph represents a clear violation of the view used by reductionism. In this representation of energy flows, the output comes first than the input!

It is time to get back to the theoretical concept of Net Energy Analysis. This concept says that in the process of exploitation of a PES, it is ***the net gain of energy carriers delivered to society*** that matters. We may have a very large PES to be exploited – e.g. huge amount of solar energy reaching our planet - but this information may result irrelevant: the pearls dispersed in the sea, or the coins lost in the sofa can represent a valuable treasure when considered as an aggregate set, but if the cost of their finding and gathering is higher than the net return, they do not represent an effective economic resource. Adopting the same reasoning we can say that ***also the assessment of the generation of the gross output of EC*** is totally irrelevant. We can generate a large supply of energy carriers from a given PES, but then if 99% of this flow has to be re-invested in the production process, the net supply for society can result totally negligible.

After accepting the wisdom proposed by Net Energy Analysis if we frame the analysis of the exploitation of a PES in terms of a chicken-egg process – as illustrated on the right side of Fig. 2 - then we have to accept an additional distinction to be made. That is, after the first distinction between PES and EC, and the second distinction between Joules of "gross supply of EC" and "net supply of EC" to the society *we have to deal with a third distinction!*: Joules of "output" and "input" of EC (a characteristics of the exploitation process itself).

The need of making these three different distinctions is directly related to the confusion flagged by Georgescu-Roegen. If we want to analyze in quantitative terms, the various factors determining the overall conversion PES → Net supply of EC we have to consider three distinct qualitative differences: (i) Joules of PES are different from Joules of EC; (ii) Joules of EC Output are different from Joules of EC Inputs; (iii) Joules of the Gross Supply of EC are different from Joules of the Net Supply of EC. As illustrated below, the implications of these differences can become crucial when exploiting a PES of a low quality.

After adopting these three categories, the chain of energy losses encountered when moving from Joules of PES to Joules of Net EC can be represented as follows:

PES/Net EC = (PES/"Gross EC") x ("Gross EC"/Net EC")

A numerical example of application of the Net Energy Analysis using this set of three distinctions is given in the upper graph of Fig. 3. The numerical values refer to the year 2003 for Spain. By adopting this graph which addresses the implications of the internal loop of "energy for energy", we can generate several benchmark values:

(i) Output/Input Ratio; (ii) Net Supply/Input; and (iii) Gross/Net ratio

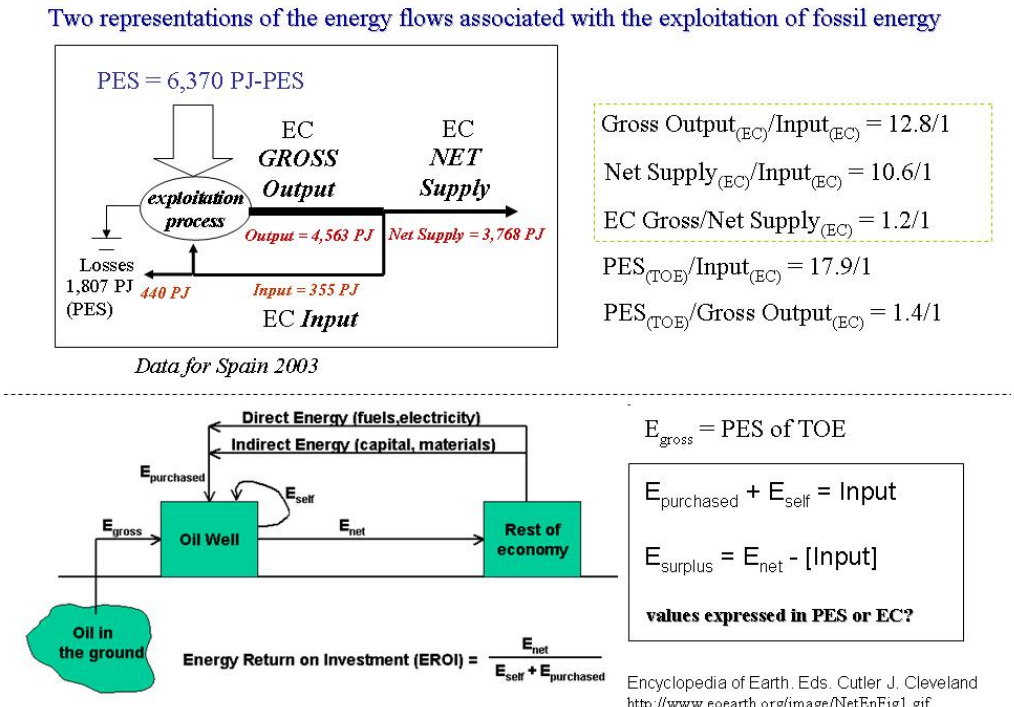


Fig. 3

These benchmark values can be used to address the issue of quality of primary energy sources. However, before getting into an analysis of the quality of the PES based on this set of benchmarks, we would like to flag the existence of a diversity of analytical frameworks adopted and proposed in the field of energetics. For example, in the lower graph of Fig. 3 we reproduce the scheme of accounting to calculate the EROI proposed by Cutler Cleveland (Cleveland, 2008 as cited in the encyclopedia of the earth) (Energy Return On the Investment will be further explained in Section 3). In relation to this accounting framework we can individuate immediately three differences with the approach proposed here:

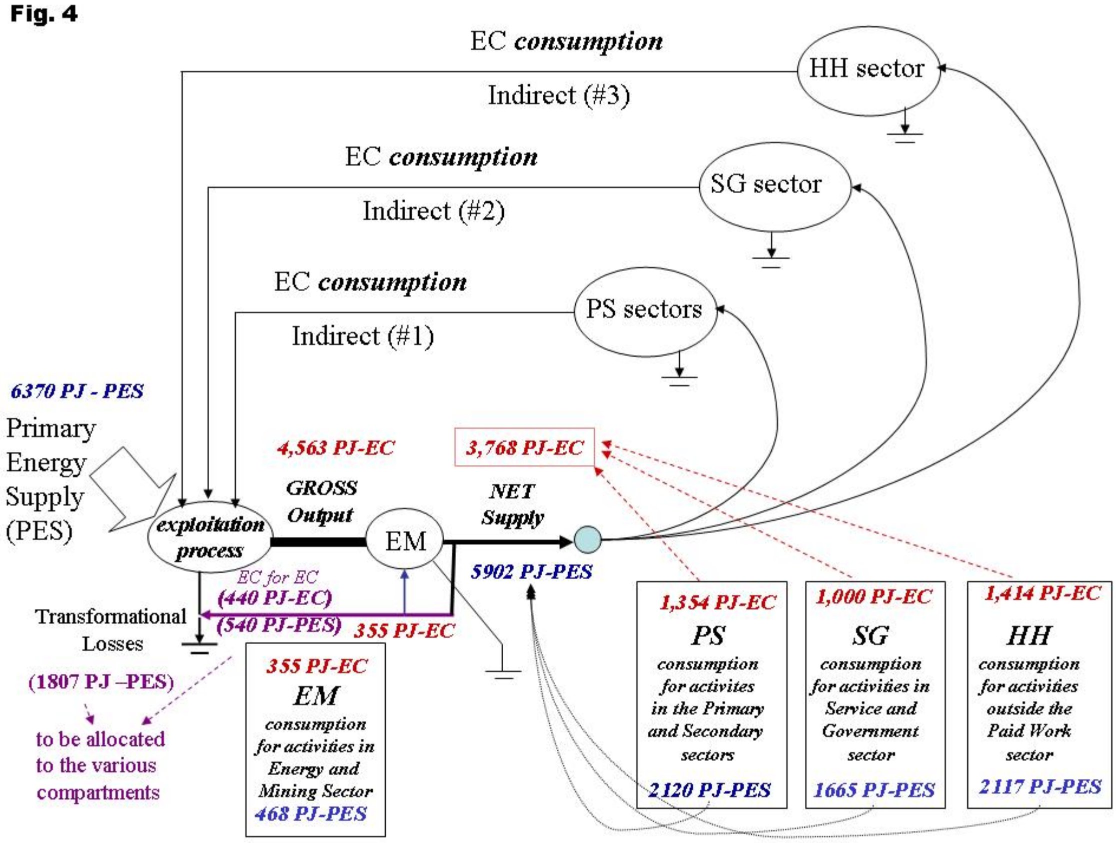
(1) in this representation the label "E_{gross}" is used to indicate the Joules of PES. The flow which is labeled as E_{net} is ambiguous in its definition. In fact, within the proposed accounting scheme there is another flow labeled as "$E_{surplus}$" which is defined as "E_{net}" MINUS "($E_{purchased}$ + E_{self})". This definition would suggest that the flow which is labeled as "E_{net}" is in reality what is called "Gross EC" in the upper graph of Fig. 3. May be the label NET is a remnant of the confusion flagged by Georgescu-Roegen in 70´ (related to the need of making a distinction between Joules of PES and Joules of EC). Accepting this explanation, we can establish a relation among the labels in the two graphs as follows: (i) E_{gross} → PES; (ii) E_{net} → EC-Gross; (iii) ($E_{purchased}$ + E_{self}) → EC-Input; (iv) "$E_{surplus}$" → EC-Net Supply;

(2) in this representation there is not specification of the type of energy form of reference to be used for the quantification of these flows. The three terms used to calculate the EROI are "E_{net}", "$E_{purchased}$", "E_{self}" which are very likely to be Energy Carriers (in our analysis). But if this is the case, this would imply a mission impossible for an accounting having the goal of addressing the relation over quantities of PES and EC, since this framework does not contain all the information needed to establish a

relation – in quantitative terms – across the various assessments. How many Joules of PES are associated with this ratio?;

(3) in this representation the calculation of the input is determined by the sum of two arrows coming back from "the rest of the economy" - two categories labeled as: (i) "direct" - which are inputs of energy carriers; and (ii) "indirect" – which are energy carriers used in the rest of the economy. Therefore these inputs may refer to consumption of energy carriers, which are *embodied* in technology and services required for the operation of the energy sector or the equivalent of these inputs (calculated in either PES or EC equivalent). This representation is too generic to be operational and could lead to an infinite regress. Since socio-economic systems are autopoietic systems (Maturana and Varela, 1987 - they are making themselves . . .) all the energy consumed in a society is used directly or indirectly to perform each one of the functions expressed by a society (Giampietro and Mayumi, 2009). For example, the making of a fiction movie can be considered as an indirect expense of energy in society, which is useful for the wellbeing of the workers of oil wells. For this reason, in order to avoid an infinite recursive loop, in which everything depends on everything else, it is necessary to organize the representation of the autocatalytic loops across different hierarchical levels, in relation to different set of functions. An example of this approach is illustrated in Fig. 4. Within this scheme, we can define as DIRECT the flow of energy carriers used in the Energy Sector to generate a Gross Supply of energy carriers. Then we can have a series of different definitions of INDIRECT energy consumptions.

Fig. 4



Indirect #1 – the flow of energy carriers required to make the capital goods and the infrastructure required by society (spent in the Primary and Secondary sectors);
Indirect #2 – the flow of energy carriers required to provide the services and controls required by society (spent in the Tertiary sector);
Indirect #3 – the flow of energy carriers required by the household sector (the final consumption sector) to guarantee the reproduction of human activity.

This segmentation across hierarchical levels makes it possible to avoid the infinite recursive loop. That is, we can decide to stop the accounting of the embodied energy going into the energy sector to a particular level, before reaching the level of the whole society, engaged in the reproductive autocatalytic-loop. It should be noted that the energy consumption of the various compartments of the society included in the representation of Fig. 4 can be characterized using two non-equivalent assessments of energy consumption. That is, by using data expressed in either: (i) PJ of PES; and/or (ii) PJ of EC. We will explain later on, the additional complication in the mechanism of accounting required to generate this parallel assessment.

The definition of different compartments of society (EM = Energy and Mining Sector; PS = Primary and Secondary Sector; SG = Service and Government; HH = Household Sector) reflects the expression of different functions in society. Since the profile of allocation of hours of human activity across these compartments is not analogous to the profile of allocation of energy consumption, different socio-economic compartments must operate at different power levels. With power level we mean the specific pace of Joules of energy carriers (or Joules of PES) consumed per hour of human activity spent in each compartments. This is discussed more in detail in the next section.

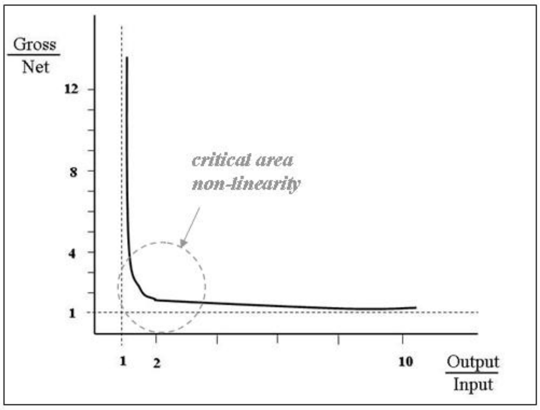
Let's now get back to the discussion over the relevance of the distinctions proposed in the upper part of Fig. 3 between:
(1) the ratio "output"/"input" of energy carriers; and
(2) the ratio "gross"/"net" supply of energy carriers.

The importance of this distinction can be appreciated by looking at the graph illustrated in Fig. 5 (from Giampietro and Mayumi, 2009).

Output/Input = Gross/(Gross – Net)

Internal Consumption: Input = Gross - Net

$$\text{Gross/Net} = \left[(\text{output/input}) \times \frac{1}{(\text{output/input}) - 1}\right]$$



Giampietro and Mayumi (2009) Figure 5.4 p. 125

Fig. 5

For values of the ratio “output”/“input” larger than 10/1 the reduction of the supply of EC associated with the loss “gross”/“net” is negligible. Looking at the values for Spain in 2003, in the upper graph of Fig.3, it can be observed that the Output/Input value is 12.8/1. This value is far from the critical area of non linearity associated to large increases in the Gross/Net Ratio (when Output/Input value is below 2/1). In this situation dealing with the conceptual difference between Gross and Net supply is not important since the difference between gross and net is small (Gross/Net = 1.2/1). Put in another way, when dealing with a “*high quality*” PES, the internal loop of energy carriers required to make energy carriers, does not affect the net supply coming out from the exploitation of the PES much. Probably this explains why the distinction between - (i) PES vs Gross EC; and (ii) Gross EC vs Net EC - was not recognized as a relevant distinction to be made in the recent past even by those working in the field of energetics. In fact, in the last 100 years humans have been dealing with the exploitation of very high quality PES – e.g. fossil energy. When dealing with fossil energy the quantitative estimate of the gross supply of EC can be used as an estimate of the net supply of EC. In fact a difference of more or less 15% in the value of this flow may very well be inside the error bar associated with the quantitative assessment. However, as soon as the “output/input” ratio of the energy carriers goes below the threshold of 2/1, the internal losses of energy to be spent to produce energy will determine a non-linear increase in the difference between gross and net supply. Looking at the curve in Fig.5 we can see that below the threshold of 2/1 the increase of internal consumption becomes no longer bearable, making any hypothesis of exploitation of PES having an output/input ratio around this value not feasible.

The analysis of the implications of a low quality PES is visualized in Fig. 6, where the framework given in Fig. 3 is applied to the analysis of the production of ethanol from corn.

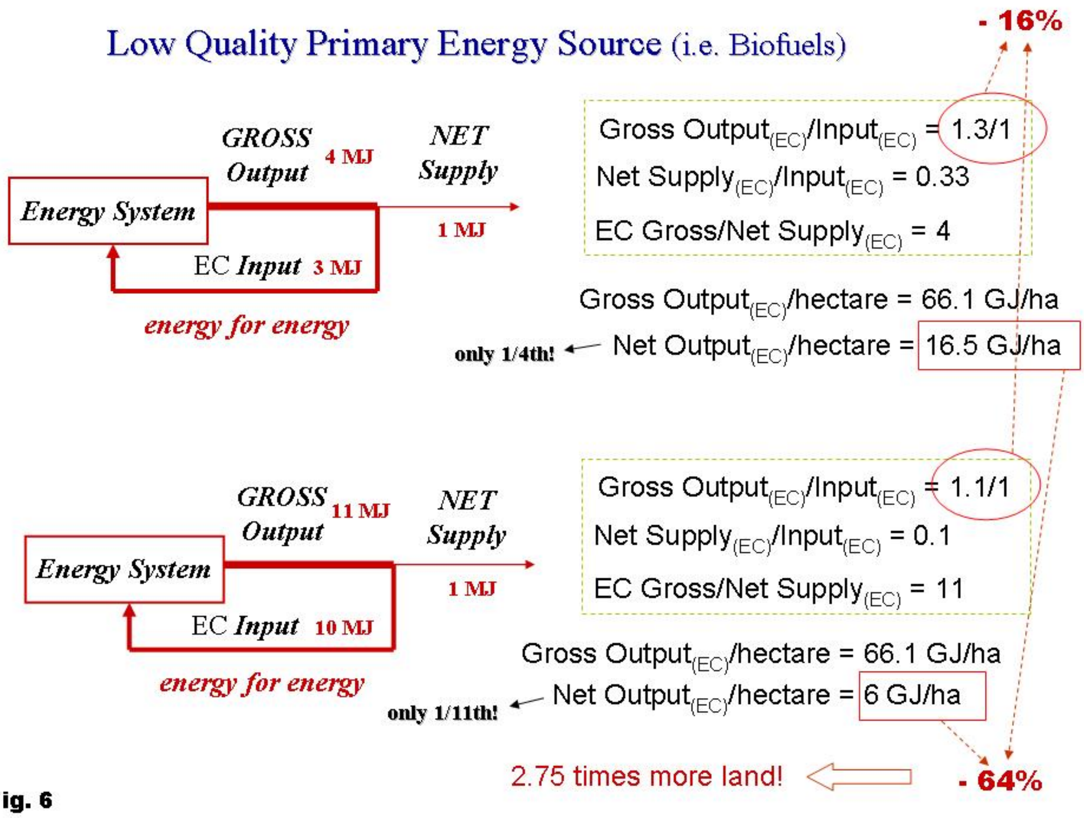


Fig. 6

In this example, we are adopting: (1) on the upper graph a generous assessment of the output/input ratio = 1.33/1 (MJ of energy carriers output *vs* MJ of fossil Energy Carriers getting in); and (2) on the lower graph a more realistic assessment of the output/input ratio = 1.1/1. For a discussion of these values see Giampietro and Mayumi (2009).

There are three points to be driven home from the information given in Fig. 6:

(1) the assessment of the gross output (what is found in literature when reading estimates of the potentialities of biofuel) is misleading. It is not true that by operating a biofuel system we can obtain more or less 66 GJ/hectare (the standard value found in literature). Rather the net supply for society is in between 6-12 GJ/hectare. This is the net value of the supply of energy carriers that can be delivered by such a system, if we are serious about considering this as a true renewable source;

(2) the system is operating in an area of very high non-linearity, in this example a reduction of 16% in the output/input (from 1.33 to 1.11) entails a much more higher reduction (of 64%) of the density of the net supply. This non-linearity implies huge increases in the requirement of PES per unit of Net Supply delivered. In this case, when considering the requirement of land (but it could be other biophysical costs such as water, soil erosion, pesticide pollution, nitrogen leakages . . .) 11 liters of ethanol have to be produced to get the net supply of just one liter. This translates into an unbearable increase of environmental impact per unit of net supply delivered to society;

(3) a lower value of the output/input translates into the need of a very large power level in the process of exploitation. That is, in order to keep the demand of labor in the energy sector low, the energy sector has to invest an incredibly high level of technical capital per hour of work.

The combination of these three points entails that the large scale production of corn-ethanol in the USA is possible, at the moment, only because fossil energy is used as the input of the process of "energy for energy" on the bottom of Fig.4. But if this is the case one can only wonder why one should convert a given amount of Joules of oil into the same amount of Joules of ethanol generating in the process a lot of environmental impact and economic costs . . . (Giampietro and Mayumi, 2009).

Section 3. The EROI concept cannot be expressed by using a single number

3.1 Introduction

The basic rationale of net energy analysis has been clearly introduced more than a century ago (Ostwald, 1907; 1911; Lotka, 1922; 1956; Podolinsky, 1883) and since then has been re-elaborated in different forms (Cottrell, 1955; White, 1943; 1949; Gilliland, 1978; Bullard et al. 1978; Rappaport, 1971; Slesser, 1978). More recently a particular form of implementation of this rationale has been proposed using the term EROI - ***E**nergy **R**eturn **O**n the **I**nvestment* - by Charlie Hall and Cutler Cleveland (Cleveland et al. 1984; Hall et al. 1986; Cleveland, 1992). In spite of its long history and evident relevance the theoretical concept of EROI tends to be neglected by modern energy analysts (see Cleveland et al. 2006; Kaufman, 2006; Patzek, 2006) and it is not receiving the due attention in terms of research funds (Hall et al. 2008). As mentioned earlier climate change and peak oil have renewed the interest in alternative energy sources, and for this reason this concept is finally getting back into the scientific discussion (Hall et al. 2008; 2009; Mulder and Hagens, 2008).

The rationale of EROI is very easy to explain starting from the financial concept, which has provided the inspiration: the Economic Return On Investment applied to financial investments. Since the explaining of economic concepts is easier than the explaining of energetic concepts we start from the economic version of this principle.

It is not possible to say whether the return of an investment equal to 10,000 € is good or bad, without getting additional information. It could be very good investment if this return is obtained over an equal amount invested in a year (= 100% of return in a year), it could be a very bad investment if this return is obtained after investing 1 million € over 10 years (= 1% of return in 10 years). This is to say, that a given quantitative assessment of "a give return of an investment" in order to be useful for decision making has to be "contextualized" and "scaled" by additional pieces of information:

(1) "how big is the required investment?" – this information is relevant in relation to the possible existence of internal constraints. For example, paying a loan for the purchase of a house, in the long term, can result more convenient than renting a house. However, the impossibility of getting enough money for starting the loan can imply that poor people have to settle for a least convenient form of investment related to their need of housing – renting for ever;

(2) "how much money will be gained by this investment?" – this information is relevant to define the scale of this operation. At times it is possible to have very large gains, but only on a very limited scale – e.g. winning money playing poker with your children. Therefore, it is important to contextualize the overall size of the exploitation process. A spider can get a very high return on its energetic investment (the making of a spiderweb). However, this type of PES would not be relevant for powering the US economy;

(3) "how quick I will get the invested money back?" – in financial operations this is the most important question. In finance as in life "*time is money*" and there are no "*free meals*". Any investment has an opportunity cost and therefore in order to assess the convenience of a given "return" one has to contextualize the expected return, in relation to the specific opportunity cost of the investor. In turn this opportunity cost will depend on the type of society in which the investor is operating. The very same activity - e.g. a barber shaving a person – will imply the generation of a different amount of added value, if performed in New York City or in a rural area of India (Goodland et al, 1992). In fact, the same hour of working time in shaving does have different opportunity costs and therefore different economic costs in societies associated with the expression of different metabolic patterns.

When looking at these three pieces of information it is obvious that we cannot convey all the information which should be associated with the concept of Return On the Investment by using a single number – e.g. a ratio between two flows of energy such as an output/input ratio. In fact, such a ratio is would be: (i) without scale; (ii) without any reference to the power level at which both inputs and outputs are operating (pace of the flows); and (iii) based on two homogeneous energy quantities (e.g. either Joules of EC output/Joules EC input or PES output/PES input). Therefore, such a ratio cannot address the qualitative differences which are affecting the overall ratio PES/net EC.

As discussed before, the information about: (i) the scale of the net supply to society and the total requirement of PES; (ii) the power level to be achieved in the Energy Sector in relation to the structure of society is essential to study whether the exploitation of a given PES is either feasible or desirable for a given society. A simple number, referring to a ratio of two unspecified energy flows associated to the exploitation of a given PES cannot be used for this task.

Finally, we arrived to the third tricky point to be discussed in this section. *It is impossible to discuss of the quality of an energy source, if we do not frame this analysis of quality against the characteristics of an expected metabolic pattern of the society*. Human feces can be a very valuable energetic input to rural communities – i.e. a good source of nutrients for agricultural production - but they do represent a major problem (and energy cost), in modern cities, since the excessive density of this flow transforms feces into a polluting flow requiring a special treatment. The different role that human feces can play in a given society is not due to the intrinsic characteristics of human feces, but simply to the difference between the relative density of two flows: (i) the pace required by society; and (ii) the pace supplied by the specific source.

For this reason, in order to discuss of the quality of energy sources it is essential to be able to visualize and quantify the characteristics of the metabolic pattern in two independent ways:

(i) definition from the demand side - the size and the paces at which energy flows have to be consumed by the different sectors of a society, in order to preserve existing socio-economic structure and relative functions (what is needed); and

(ii) definition from the supply side - the size and the pace at which at which energy flows can be generated by the energy sector to support the required set of energy transformations going in the society (what can be delivered).

We claim that for the first task it is better to use an energy accounting based on Joules of EC, and for the second task is better to use an accounting based on Joules of PES.

3.2 The metabolic pattern on the demand side: why "time is money"

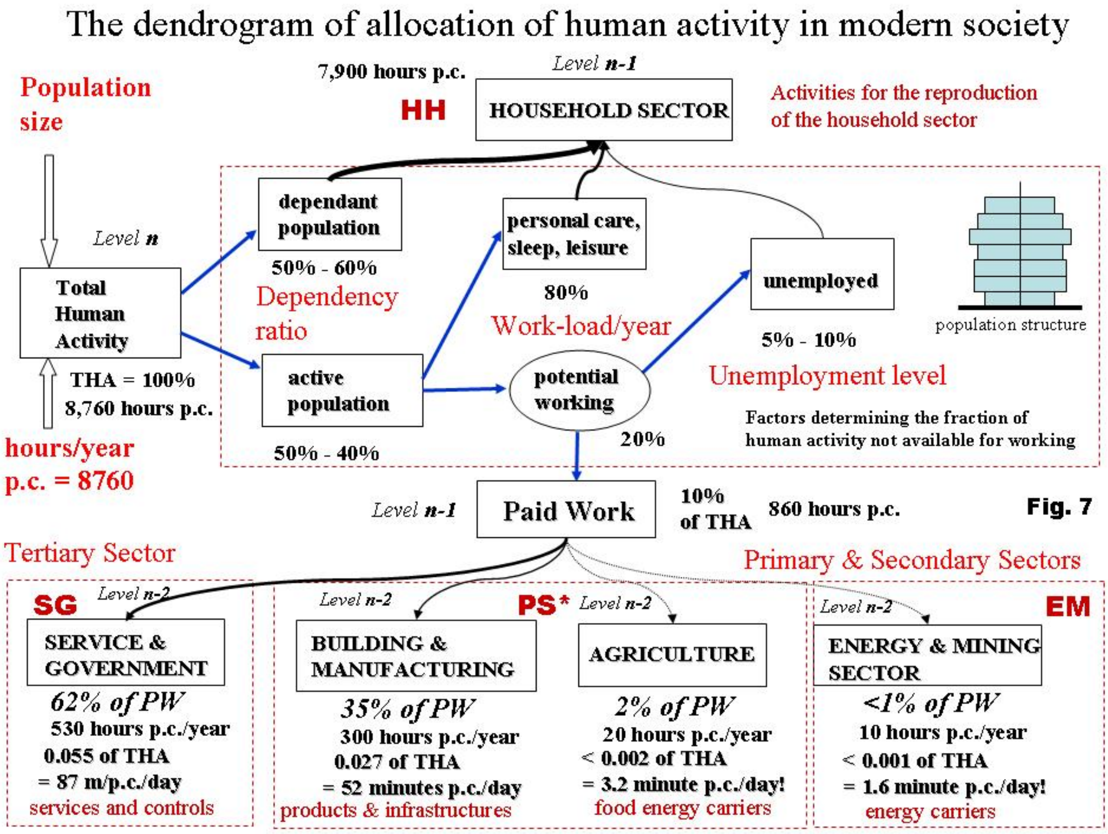
The concept of metabolic pattern of a modern society (Giampietro and Mayumi, 2009) is based on the idea of the existence of a forced set of relation between: (i) the size of the different compartments of a socio-economic system, expressed in hours of human activity; (ii) the required size of energy flows, required to perform the various functions expected by these compartments; and (iii) the resulting forced profile of power levels for the various flows of energy across compartments.

The information about points (i) and (ii) refers to the characteristics of compartments of the society observable at the hierarchical level of the individual elements; whereas the information about point (iii) refers to the characteristics of the whole society (an emergent property of the whole). This idea of characterizing the energetic metabolism of complex systems is based on the approach proposed by H.T. Odum (1971; 1996) within system ecology to study the forced relation between: (i) the size of the different compartments of an ecosystem, whose size can be expressed in biomass; (ii) the require size of energy flows required by the various compartments to perform their functions, expressed in solar energy equivalent; and (iii) the resulting profile of power levels for the various flows of energy across compartments (embodied solar energy per unit of biomass). The adaptation of this analytical approach, originally developed for natural ecosystems, to the analysis of the metabolism of modern society has been carried out using the conceptual Fund-Flow model developed by Georgescu-Roegen (1971; 1979). A detailed description of the theoretical framework is available in Giampietro and Mayumi (2009).

There are general features which can be expected when studying the metabolic patterns of modern societies in relation to the division of human activity over different functional and structural compartments. For example, because of ageing, post-industrial societies have a large dependency ratio (non-working population/working population) and because of the level of economic development there is a high fraction of the work force which is employed in the service sector. This translates into a dramatic reduction of the availability of working hours in the Primary and Secondary sectors, especially in those primary sectors in charge for producing basic energy input such as agriculture (food energy) and energy and mining (commercial energy).

It is possible to describe this feature by studying a dendrogram of the profile of allocation of hours of human activity in a modern society. In fact, as illustrated below, the particular structure of this dendrogram implies the existence of severe internal constraints on the feasibility of the resulting metabolic patterns.

The numbers indicated in Fig. 7 represent a standard set of values expected in a modern industrialized society. Let's first start with the conceptualization of the various activities performed in a society, based on the definition of different functional compartments. The total size of a socio-economic system – defined at the hierarchical *level **n*** – is represented as the total amount of hours of human activity per year. This can be labeled as Total Human Activity (THA) and defined as: THA = population * 8,760 hours in a year (24 hours/day * 365 days/yr - the left box of Fig. 7). This amount of human activity per year is then divided in two compartments - defined at the hierarchical of the lower level of *level **n-1***. The two compartments are: (i) Household (HH) - hours of human activity per year invested in activities outside paid work; (ii) Paid Work (PW) - hours of human activity per year invested in activities performed within the Paid Work sector.



We can further split the hours of human activities in the PW compartment – defined at the hierarchical *level* ***n-1*** - into three amounts of hours of human activity referring to sub-compartments, which are defined at the hierarchical *level* ***n-2*** (inside the PW box). These three compartments are: (i) EM – Energy and Mining Sector; (ii) PS* - Primary and Secondary sectors minus the Energy and Mining Sector (PS* includes the Agricultural Sector and the Building and Manufacturing Sector); (iii) SG – Service and Government. To establish an effective multi-level matrix the total amount of hours of human activity must remain constant at each level (level n; level n-1; and level n-2) and to be equal to the sum of the hours of human activity accounted in the various sectors:

* On the interface *level* ***n***/*level* ***n-1***: $THA = HA_{HH} HA_{PW}$
* On the interface *level* ***n-1***/*level* ***n-2***: $HA_{PW} = HA_{EM} HA_{SG}\ HA_{PS*}$

This multi level matrix of accounting is based on various quantities of hours of human activity allocated in different compartments, defined at different hierarchical levels. It makes it possible to express the resulting profile of allocation of hours of human activity per year on “per capita basis”. This requires dividing the total amount of hours spent in each compartment by the number of people in the society.

This profile of distribution of hours is illustrated by the arrows indicating the amount of hours of human activity per capita, invested in the various compartments. Out of the 8,760 hours per capita year of human activity (THA p.c. defined at the *level* ***n***), 7,900 hours p.c. go into the reproduction of households – that is 90% of THA goes into HH at the *level* ***n-1*** - and only 860 hours p.c. – that is 10% of THA - goes into the activities performed in the PW sector (at the *level* ***n-1***). After further splitting these

hours, moving to a lower level (at the *level* ***n-2***), into hours of activities allocated into the three sub-compartments we are forced to realize the remarkable compression in the availability of working time, which is required to carry out essential functions for modern societies in the PS sector:
(A) in relation to the generation of an adequate supply energy carriers in EM – less than 0.1% of THA goes into EM (meaning that in 1 year, out of 8760 hrs of THA per capita, 10 hrs per capita are invested into this sector) – that is, the entire amount of energy carriers that is consumed per capita, translating into an accounting of 24 hours in a modern society, must be made available by 1.6 minute of work in the energy sector;
(B) in relation to the generation of an adequate supply of food in AG – less than 0.2% of THA goes into AG - that is the entire amount of food that is consumed per capita in a year in a modern society must be made available by less than 20 hours of work in the agricultural sector;
(C) in relation to the generation of an adequate supply products and material infrastructures in PS* - only 2.7% of THA goes into PS*.

Put in another way economic development entails a dramatic reduction of the hours of working time per capita per year in the Primary and Secondary sectors of the economy, which in turn entails the forced adoption in these sectors of a set of energy transformations – technological processes - based on very high power levels (= low requirement of labor in relation to the tasks to be performed).

3.3 The metabolic pattern on the supply side: the profile of power levels

At this point, after having defined a multi-level matrix of compartments mapping useful functions for society, we can map the various flows of energy associated with the activities of the various compartments. These flows of energy, which reflect the technology used in the structural organization of socio-economic activities, can be mapped against the multi-level matrix of hours of human activity. For this task, we can start by considering the total flow of energy consumed by the society per year – Total Energy Throughput (TET) and then divide this flow over the compartments of the multi-level matrix, generating in this way, a profile of energy expenditure in the various sectors corresponding to the dendrogram used in Fig. 7. An example of this division of energy in compartments has been given in Fig. 4 for Spain.

Because of the needed distinction between PES and EC, we can carry out a *parallel accounting* (following the scheme presented in Fig. 1 and Fig. 4) of how the Total Energy Throughput of a society is spent. That is TET can be measured both:
(i) in *Joules of PES equivalent* and (ii) in *Joules of Energy Carrier (EC) Equivalent*.

An example of this approach is given in the right box of Fig. 8, in which we use a generic expected value for a rich industrialized country: 300 GJ of "PES equivalent", per capita/year; which translates into approximately, 200 GJ of "EC equivalent" per capita/year.

When we express the Total Energy Throughput of a Society using Joules of EC equivalent we can study the efficiency of the conversions of flows of EC into end uses, in relation to the functions to be performed by the society. This analysis deals with the perception of events from the inside of the black box – internal constraints to the feasibility of the metabolic pattern. Different compartments do express different functions. Thus, we can divide the overall flow (TET expressed in EC equivalent), in a set of flows going through the set of compartments of human activity – ET_i - defined across the different hierarchical levels (*level* ***n***, *level* ***n-1***, *level* ***n-2***) over the multilevel matrix. The definition of these flows corresponds to the definition of the set of functional compartments adopted in the definition of the multi-level matrix of human activity:

* On the interface *level* **n**/*level* **n-1**: $TET = ET_{HH} ET_{PW}$
* On the interface *level* **n-1**/*level* **n-2**: $ET_{PW} = ET_{EM} ET_{SG}\ ET_{PS*}$

The metabolic pattern of society and the resulting profile of power levels

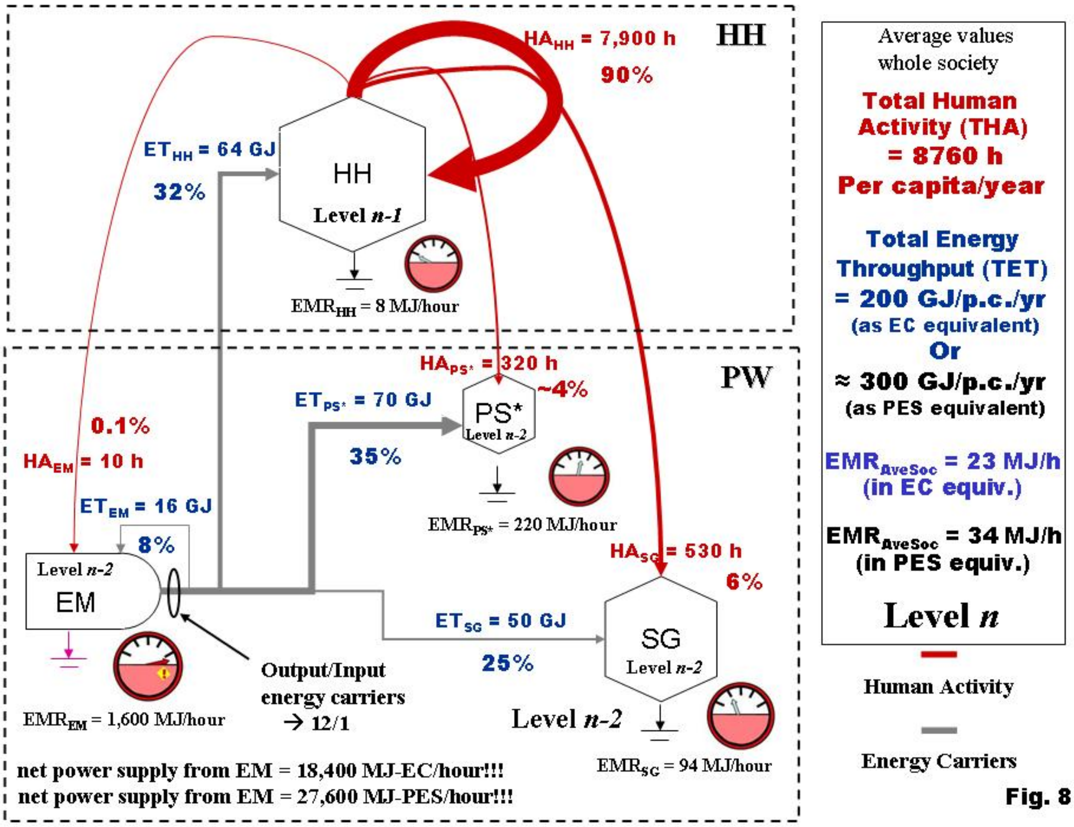


Fig. 8

On the other hand, when we express the Total Energy Throughput of a Society using Joules of "PES equivalent" (the assessment of 300 GJ of PES p.c./year) we can compare the overall energy consumption of a society in relation to the biophysical requirements associated with the metabolic pattern – the total demand of PES on the environment (to be matched either by local favorable gradients or by imports). This analysis deals with the perception of events from the outside of the black box – external constraints to the feasibility of the metabolic pattern. Moreover keeping the accounting of TET in Joules expressed in "PES equivalent" also allows to keep the compatibility of this quantitative analysis with data given by International Statistics and other well established databases – i.e. the common way of accounting for national energy consumptions.

The internal constraints of congruence over the profile of allocation of hours of human activity and MJ of energy do determine a forced relation of congruence between: (i) the relative size of fund elements (the size of the compartments expressed in hours of human activity); (ii) the relative size of the flows indicating consumption of energy (the amount of energy required to carry out the various functions associated with the different compartments); (iii) the specific power level (the ratio energy per hour of human activity), which must be achieved in each compartment.

The resulting metabolic pattern for a typical rich developed country then is as shown in Fig. 8 with a practical example. In relation to TET (Total Energy Throughput) for the Societal Average we propose the following benchmarks:

* 200 GJ/year (or 23MJ/hr) – when "energy consumption" is expressed in EC equivalent;
* 300 GJ/year (or 34 MJ/hr) when "energy consumption" is expressed in PES equivalent.

The corresponding energy flows expressed as Energy Throughput (ET_{iB}) measured in Joules of EC, for each specific sector is then distributed across the levels by maintaining an overall congruence across each hierarchical level. i.e. To avoid too much confusion we provide an example based only on quantitative assessments expressed in Joules of EC. The sum of the energy throughput in the elements making up PW at Level n-2 [(i) ET_{EM} – 30 GJ (15% of TET); (ii) ET_{PS*} - 70 GJ (35% of TET); (iii) ET_{SG} – 40 GJ (20% of TET)] is equal to the sum of the total energy throughput in Level n-1 [ET_{PW} – 140 GJ]. The sum of the two elements defined at the level n-1: ET_{PW} (140 GJ) and ET_{HH} (60 GJ) makes up, at the Level n, the total TET in EC (200 GJ).

However, a more elaborated method of accounting based on matrices (explained below) can make it possible to study the relation between: (i) integrated demand of different EC mixes of carriers to be used by the different sectors; (ii) the specific mix of PES used in the energy sector for the supply (the view given in Fig. 1) over this representation of the metabolic pattern.

After having allocated the fraction of the total human activity and the total energy throughput to the various compartments, it becomes possible to study the profile of power levels for each compartment. In Fig. 8 this power level is indicated by the gauge symbols indicating the value of Energetic Metabolic Rate (EMR) measured in MJ/hour (again in MJ of EC) – calculated by the consumption of energy carriers within that sector divided by the specific hours allocated to that sector. This benchmark can be applied across hierarchical levels: we can define an $EMRB_{SA\ level\ n}$ (= 23 MJ/hour) at the level of the whole society (*level **n***). By remaining at this hierarchical level, this average power level (pace of energy consumption Average Society) can be used to compare different societies (at the level of the whole). However, we can move across levels in different compartments defined inside the society and find that this value changes dramatically. The expected value of EMR is much lower than the societal average in the HH compartment ($EMR_{HH\ level\ n-1}$ = 8 MJ/hour) and it is much higher in the Energy and Mining Sector ($EMR_{EM\ level\ n-2}$ = 1,600 MJ/hour!). Moreover, the net supply of energy that the energy and mining sector has to generate to maintain the functions of such a society can also be calculated. After subtracting the energy used for the Energy and Mining sector itself (200GJ -16GJ), the net power supply that the energy and mining sector has to handle is 184GJ (per capita per year) using only the 10 hrs (per capita per year) of work allocated in this sector. This entails the ability of yielding a net power supply of 18,400MJ/hr expressed in EC. An approximate equivalent of this expressed in PES values would yield 27,600 MJ/hr in PES.

The ability to discover and check the existence of critical threshold values and bottlenecks determining internal constraints, which do determine the feasibility of the exploitation of a given PES, is exactly the special feature which makes very useful the concept of metabolic pattern of modern societies. In a modern society the metabolic characteristics of the whole depend on the metabolic characteristics of the parts and viceversa.

3.4 Implication of the metabolic pattern: matching the demand side with the supply side

So far, the process of economic growth has entailed a continuous simultaneous reduction of: (i) the fraction of hours of human activity invested in the PW sector versus the hours of non-working (dependent population, leisure, education). The combination of these two trends translates into less hours of paid work per capita per year; and (ii) the fraction of hours of human activity invested in the primary sectors within PW has been continuously shrinking – e.g. the fraction of the work force dealing with both agriculture and the energy sector. This change implies less hour of work per capita per year in the PS sector. For this reason, for a modern society it is essential to have an energy sector which can be operated using only a tiny fraction of the work force – around 1% of the work force.

Going back to the metabolic pattern of a modern society illustrated in Fig. 7, we can notice that the ES has to process/deliver the total amount of energy consumed by society, while using only 1/1000th of human activity (1% of the 10% of THA, which is about 1.6 minute p.c. per day!). This evolution of the metabolic pattern of modern society has been made possible by the extremely high quality of fossil energy as PES, which translated into a progressive elimination from the work force of both workers in agriculture and in the energy sector. In particular, by using the three quality checks discussed in relation to the concept of EROI we can describe this high quality as follows:

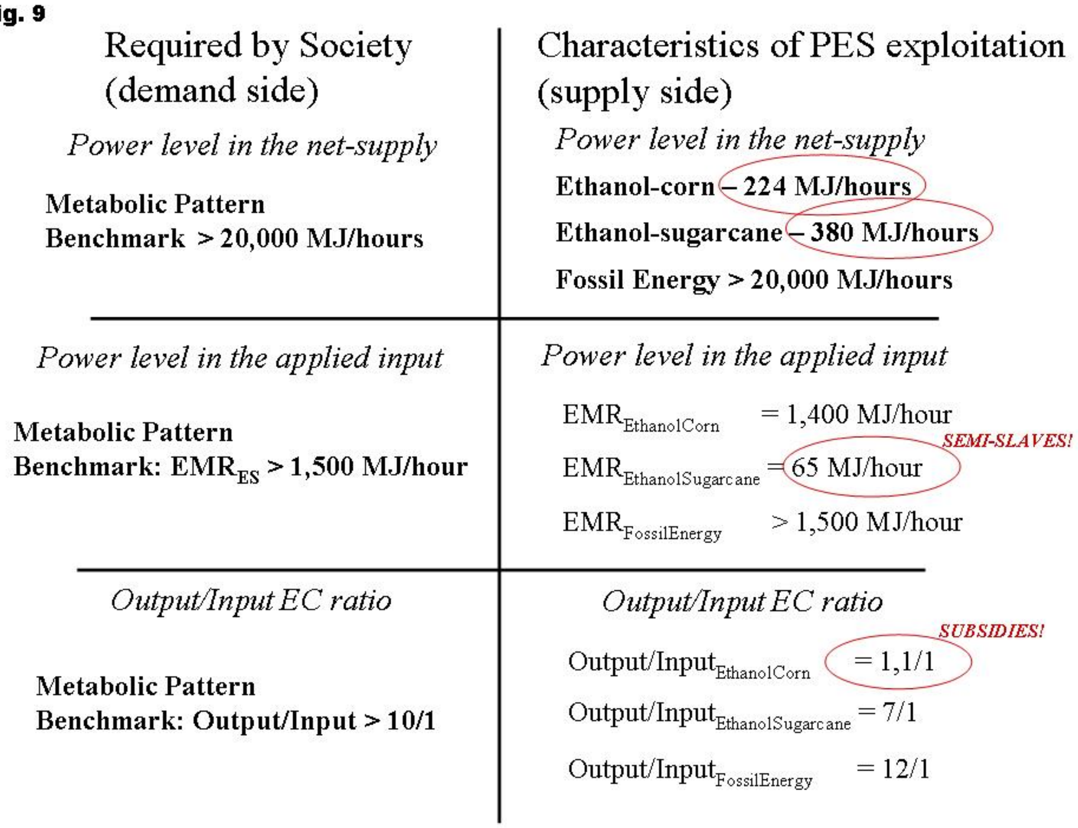
(1) fossil energy is a stock-flow type of resource. This implies that so far (before peak oil) the richest part of humankind did not experience any biophysical problem to continuously increase the overall size of the flow of PES to be used. That is, in the oil era, for industrialized countries the variable "size of the population" has never been influenced by availability of energy. Even if increasing the population implies reducing the amount of land per capita, oil provided a "temporary emancipation from land" (Mayumi. 1991). As a matter of fact, world population doubled (from 3 billion to 6 billion) in the last 30 years while the amount of consumption of energy per capita has kept increasing!;

(2) fossil energy generates a dense supply of energy carriers. When talking of fossil energy, the extreme concentration of the energy flows makes it possible to carry out huge investments for their handling. The average power level in the ES sector is 1,600 MJ/hour (EMR measured in Joules of EC) and no matter how big is the technical investment to be done in the exploitation of fossil energy, this investment can always be afforded (both in economic and biophysical terms). Just let's consider the huge coal machine working in open mines, or the size of supertankers crossing the sea, or the amount of energy transported per second in international pipelines or the level of power in modern electric distribution grids per hour of work to have an idea of the power level possible when handling fossil energy EC;

(3) when exploiting both concentrated stocks of fossil energy and "dense" energy carriers, it is possible to reach simultaneously: (i) high power levels in the energy sector on both side – processing the input (EMR > 1,500 MJ/hour) and delivering a very large net supply (NetPowerSupply >18,000 MJ/hour); (ii) a high output/input of energy carriers (e.g. 12/1) – see Fig. 8.

Let's now use the characteristics of the metabolic pattern illustrated in Fig. 8, which is based on benchmarks typical of a rich post-industrial country, to assess the quality of agro-biofuels as an alternative PES. For this exercise we use data referring to the two large-scale processes of exploitation available at the moment: ethanol from corn in the USA and ethanol from sugarcane in Brazil. The characteristics of these two systems are described in Fig. 9 (from Giampietro and Mayumi, 2009).

Fig. 9



The benchmarks given in Fig. 9 refers to the integrated set of constraints (internal and external constraints) determining the feasibility of large-scale generation of agro-biofuels having the goal to power the metabolic pattern of a modern post-industrial society. These numerical values clearly indicate a systemic lack of feasibility of this option, since the characteristics of the supply side (the net supply of energy carriers from the energy sector to the society per hour of paid work) are not consistent with the characteristics of the demand side (the metabolic pattern of consumption of energy carriers in the society – the requirement of both "energy carriers" and "hours of working time" in the various economic sectors). The values used for assessment are based on the system of accounting illustrated in Fig. 2 (right graph) and indicate: (i) the net supply of energy carrier (liters of ethanol) for USA; and (ii) an optimistic analysis of ethanol from sugarcane in Brazil (more details in Giampietro and Mayumi, 2009).

The different factors considered in Fig. 9 clearly indicate that none of the two systems of production is even close to be feasible. Please note that in this feasibility check, we are not even considering the external biophysical constraint associated with land requirement [the net supply of energy carriers on the supply side in the order of 0.02 W/m^2 - 0.4 W/m^2 (liters of ethanol) versus a density in consumption in the order of 7 W/m^2 - 70 W/m^2 (fossil energy fuels)]. The set of constraints considered in Fig. 9

refer only to the power levels per hour of work. Both systems Ethanol-Corn in the USA and Ethanol-Sugarcane in Brazil are not feasible since they cannot deliver the required net supply of energy carriers per hour of labor in the energy sector.

This situation of unfeasibility, however, is determined by a different combination of factors. In the case of Brazil the output/input of energy carriers is acceptable (7/1) but it is the extremely low power level (< 70 MJ/hour of EMR), which makes this solution not compatible with the benchmarks associated with the metabolic pattern of modern societies. With the Ethanol-Corn system in the USA we have the reverse situations. The power level is acceptable, even if low (1,400 MJ/hour of EMR), but it is the output/input of energy carrier which is extremely low (1.1/1).

As explained earlier this systemic problem can be associated with the low quality of the biomass as PES, since the two values ["Output/Input of energy carriers" and "EMR" power level] are related to each other. If one want to increase the power level (EMR), in order to gather a disperse flow of PES as biomass using a limited amount of labor, one has to invest a large amount of energy carriers (this is where the Output/Input plummets). On the contrary, if one wants to keep high the Output/Input by reducing the power level, then one has to increase dramatically the amount of working time to be invested in the energy sector (the EMR plummets).

Section 4. Studying the energetic metabolic pattern of modern society

4.1 Looking at the metabolic pattern simultaneously on the two sides

In the previous sections we presented three epistemological conundrums that prevented so far a successful adoption of the standard sets of simplifications typical of reductionism when dealing with quantitative analysis of the energetic metabolism of modern societies. In this section we propose a heuristic method which can be used to handle the various tricky points discussed so far. By adopting this approach it becomes possible to: (i) structure and guide – using quantitative data - the discussion over future energy scenarios (matching the metabolic pattern on the supply and demand side); and (ii) develop a more reliable method of assessment of the quality of alternative energy sources. This requires assessing the quality of the supply in relation to: (i) internal constraints - the pattern of demand; and (ii) external constraints – the biophysical limits to the exploitation of the required amount of PES of different types.

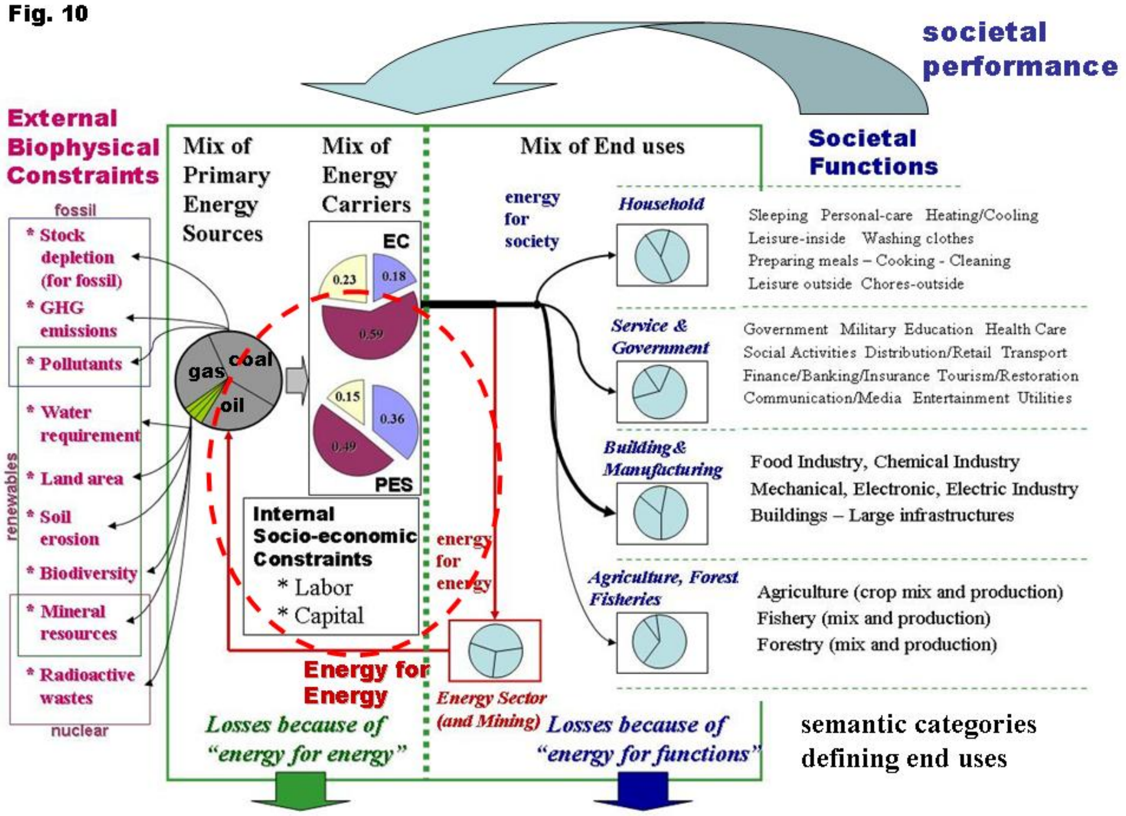
In fact, by adopting a characterization of the metabolic pattern of modern society based on the distinction between: (i) different functional/structural elements of society and (ii) different types of energy forms, one can establish a relation between:

* the set of functions expressed by a socio-economic systems (at the level n), which are mapped onto a set of compartments of human activities defined across different levels within the society;
* the set of structural organizations established in the given set of compartments, making possible to have the production and consumption of goods and services associated with societal identity;
* the set of energy transformations (defined in terms of size and power levels) which are required to stabilize the resulting metabolic pattern.

In this way, the given identity of a modern society can be associated with the definition of a multi-level matrix of functional/structural compartments. In turn this multi-level matrix makes it possible to describe in parallel the two profiles of allocation of both human activity and energy carriers over the common set of structures and functions.

In this way, we can finally deal with the big picture of the whole process of autopoiesis of society. This is crucial, since at this level we can finally address the key role played by the third type energy forms mentioned in Section 2 – the role of **end uses**. End uses (the effective delivery of energy services) are required to stabilize the process of reproduction of both structures and functions of society. In fact the label "end uses" indicate the use of energy carriers in order to perform the whole set of functions of a society, including the exploitation of primary energy sources generating the energy carriers. By closing the loop (Energy Carriers → End Uses → Primary Energy Sources → Energy Carriers) they provide the definition of "usefulness" for the set of energy conversions carried out in the EM sectors (the first set of conversions moving from PES → EC). As mentioned in Section 2, however, it is not possible to generate an exact quantitative measurement of these end uses, and this fact requires the adoption of an innovative approach (impredicative loop analysis) for such a study.

Fig. 10



As illustrated in Fig. 10 we can describe the process of autopoiesis of a society as based on a double chicken-egg process taking place simultaneously at two different scales.

at the level of the energy sector – at a small scale - the autocatalytic loop within the set of energy transformations taking place in the energy sector (the internal loop of energy for energy illustrated in the upper part of Fig. 3 and in Fig. 4). In this autocatalytic loop, energy carriers are used to generate more energy carriers, but in order to have this internal loop it is necessary to have an adequate amount of PES available (external constraints) and the capability of express the required functions powered by these energy carriers (internal constraints). The net-supply of energy carriers generated by the energy sector is then used by the other compartments of the society to guarantee the other functions required for the reproduction and maintenance of social systems (a quantitative representation of this process applied to Spain is given in Fig. 4). The strength and the power of this autocatalytic loop is constrained by two types of constraints: (i) external constraints - associated with the availability of an adequate size of PES – on the left of Fig. 10; and (ii) internal constraints - associated with the availability of labor – illustrated in Fig. 7 - and capital to be invested in the energy sector. In fact, the internal loop of energy for energy (loop 1) competes with the second loop (the larger arrow indicating the usefulness of the other ends uses for society) in terms of the given amount of hours of labor, Joules of energy carriers and investments of technical capital. This internal competition generates the stabilization over an expected metabolic pattern (relative size and power level across functional compartments) as illustrated in Fig. 8. This is where the issue of an expected profile of power levels across compartments gets into the picture. The set of internal constraints on the viability of a given metabolic pattern is generated by the existence of this competition. Within this general framework we can see that the adoption of a "low quality" PES entails a dramatic increase in the amount of: (i) energy carriers, (ii) hours of work, and (iii) technical capital; which have to be allocated to the energy sector (the internal loop of energy for energy). Since this internal loop of "*energy for energy*" is not negotiable such an increase will imply moving away these factors from the activities performed in the other sectors of the economy (in both the production and consumption of other goods and services). Therefore a low quality energy sources entails a reduction in the ability of a society of expressing the various functions illustrated on the right side of Fig. 10.

**** at the level of the whole society*** – at the large scale – we can see the autocatalytic loop within the set of energy transformation taking place in the socio-economic system seen as a whole. At this level we can observe a resonance between the two chains of transformation: "$PES_{exploitation} \rightarrow EC \rightarrow EU$" and "$EU \rightarrow EC \rightarrow PES_{exploiation}$" which is affecting/affected by the quality of PES. In this autocatalytic loop, "*end uses*" (energy services) are essential for the reproduction and expansion of the ability of a given society to define and express its own identity as socio-economic system. In practical terms this means the ability to preserve and adapt the given set of expected structures and functions. For this reason, it is impossible to define using the traditional linear approach of reductionism a quantitative analysis of an autocatalytic loop of energy (Giampietro and Mayumi, 2004; Mayumi and Giampietro, 2004). What is proposed here is the use of an innovative method based on complex system thinking – a semantically open system of representation called a "meta-grammar" (Giampietro and Mayumi, 2009; Giampietro et al. *forthcoming*) as discussed below.

4.2 Implementing a quantitative analysis based on a meta-grammar: moving from the analysis of a linear set of conversions to the analysis of an autocatalytic loop

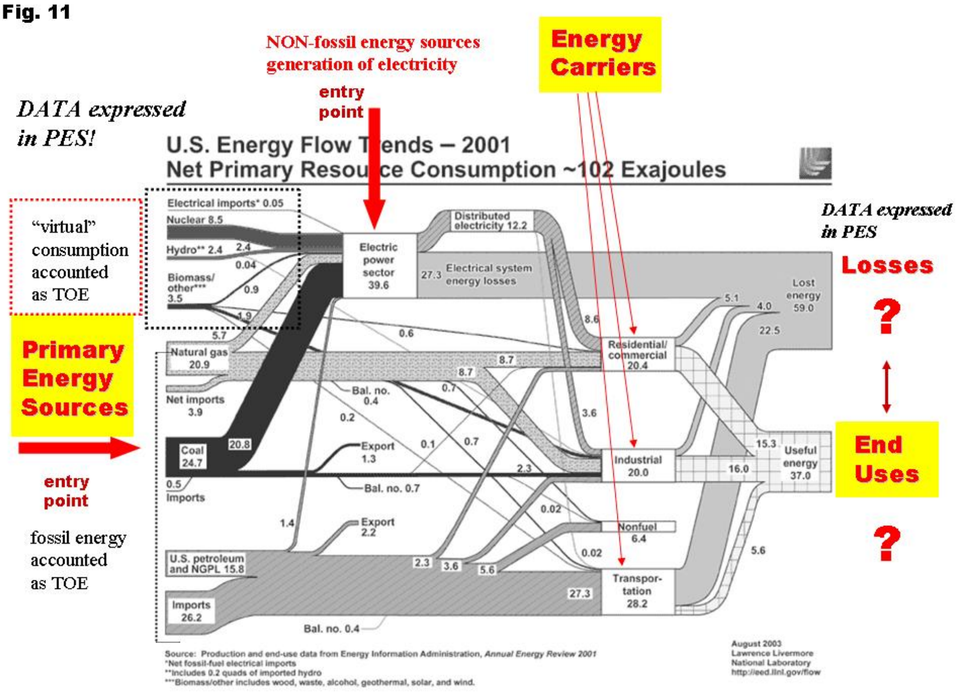
We propose here an innovative approach for quantification of energy consumption across the different compartments making up modern societies, which can be used to improve the usefulness of energy accounting and energy statistics.

First of all, let's start by the definition of the concept of grammar, which is essential for the handling of the perception and representation of complex systems. As a matter of fact, what is shown in Fig. 10 is an example of meta-grammar. A grammar is heuristic tool for organizing information (e.g. a software) consisting of various elements: (i) a lexicon (the set of all the types of variables to be used); (ii) a set of production rules (determining an expected relation among the values of different variables); (iii) a data set reflecting the definition of categories adopted in the lexicon. In spite of the elaborated description, we are all familiar with the concept of grammar since this is how the information is organized even at the level of natural languages (Chomsky, 1977; Kauffmann, 1993). Starting from the concept of grammar, we can define a meta-grammar as a set of expected relations established over a lexicon made of only semantic categories. The suffix "meta" means that this special type of grammar does not include the specification of the production rules which should be applied in the formalization of the semantic categories (when handling quantitative data). Therefore a meta-grammar is a heuristic tool helping the structuring of an analysis, which has to be tailored, when dealing with specific applications, by assigning context specific "dictionaries" to the semantic lexicon. In other terms this implies defining the specific set of conversions (energy carriers, converters, technical coefficients and relative data) to be associated to the semantic categories, in relation to the situation to be described. Put in another way, the list of functions defined for the various compartments on the right side of Fig. 10 can be translated into a set of requirement of energy carriers, hours of human activity, investments of technical capital (when describing the metabolic pattern on the demand side) – e.g. cooking in rural areas of China versus cooking in a Dutch city.

The concept of grammar entails a crucial characteristic: the possibility of generating an information space which is determined by a set of rules making possible the expression of coherent patterns; but at the same time, such an information space is not fully deterministic, before receiving a series of inputs from the person using the grammar. The very popular Sudoku game can be used as a metaphor of this characteristic. An empty Sudoku grid requires an input of information (the initial numbers to be entered in the grid) before arriving to a stage in which the identity of the remaining numbers is fully determined (when it moves from a supercritical to a subcritical state). So the Sudoku grid has a set of production rules, which have the capability of generating a deterministic information space, but only after receiving an input of data.

We can generalize this concept by saying that by using a meta-grammar we can generate a semantically open information space, which still has enough internal constraints to be able to generate coherence over numbers. That is, a meta-grammar requires an initial phase in which the analyst must provide the semantic tailoring of the perception and representation on the specificity of the system to be studied. Getting back in the grammar provided in Fig. 10, and looking at the list of the functions given on the right of the figure we can ask – what we mean with "cooking" in the investigated system? What are the energy transformations associated with human activities within residential? What are the technical coefficients both per hour and per hectare describing the agricultural production? The use of "dictionaries" – the specific formalization of the semantic category within the given society to be characterized – makes it possible to provide a quantitative specification of the perception used to define "what the system is" (the functional elements of the society) and "what the system does" (the various types of energy forms, power levels and amount of hours of human activity in each element) within the specific quantitative analysis. After a wise choice of categories and definitions of the relative compartment, one can gather enough information to generate a coherent quantitative representation of the metabolic pattern of a modern society, capable of providing useful information about external and internal constraints affecting its feasibility (more in Giampietro and Mayumi, 2009).

Fig. 11



To avoid an excess of theoretical discussions let's discuss an example of the traditional way used to represent energy transformations within a society.

The conventional take of energy statistics is illustrated in Fig. 11 and it is based on the conventional linear representation of the energy flowing within a society (the standard approach of reductionism). The "energy inputs" are entering on the left of the graph and the "energy outputs" are described on the right side of the figure. However, after the long discussions of the previous sections we can notice a few problems in this approach.

Problem #1 - There is no separation in the quantitative accounting of different energy forms. The primary energy sources are illustrated on the left side of the graph and are assessed using as PES of reference – e.g. Joules of Tons of Oil Equivalent. As a matter of fact, in order to be able to account the contribution of nuclear and hydroelectric generation, there is an estimation of "virtual consumption of Joules of TOE" equivalent to the amount of TOE that would have to be consumed to generate the electricity obtained using PES alternative to fossil energy. That is, there is a flow of Energy Carriers which enters into the system from the top (directly into the Electric Power sector), but it is accounted as a "virtual input of PES-TOE" on the left;

Problem #2 - The consumption of the three final sectors: (i) Residential/Commercial; (ii) Industrial; and (iii) Transportation, may refer to Joules of Energy carriers. This implies that the difference between Joules PES (e.g. 24.7 Exajoules of coal) and Joules of EC (e.g. 20 Exajoules spent in the Industrial sector) is represented by the losses, which are described – all mixed together - on the right side of the graph as a form of End Use!

Problem #3 - Because of this ambiguity about the accounting of energy we cannot know which fraction of the losses should be assigned to the energy consumption of the three final sectors. In fact, it is well known that the mix of energy carriers used in the chosen three sectors is quite different, therefore the losses of PES are not proportional to the three numbers indicating energy consumption in these sectors: 20.4 EJ in Residential/Commercial (30%); 20.0 EJ in Industrial (29%); and 28.2 EJ in Transportation (41%). Put it in another way, the profile of consumption over these three sectors when expressed in percentage of the total does not map onto the percentage of the total consumption (TET expressed in PES, which is 102 EJ for the whole USA) to be assigned to each one of these sectors;

Problem #4 - The definition of the three final sectors reflects historic reasons (exactly a different profile in the mix of energy carriers), but does not address the functional role played by these sectors in society. For example: (1) Residential/Commercial includes activities referring to Paid Work (Service and Government) which can include the army, the big distribution; activities referring to Agriculture; activities referring to the Household Sector (but excluding private driving, which is included in Transportation!); (2) Industrial sector includes activities referring to both building and manufacturing; (3) Transportation mixes together transport done for generating added value in PW and personal driving in the HH sector.

Problem #5 – (least but definitely not last!) due to the lack of distinction between Joules of PES and EC and the unspecified summing of different types of losses, there is not an explicit reference to the amount of energy spent in the Energy Sector - the crucial importance of the characteristics of the loop "energy for energy" cannot be addressed within this accounting scheme.

An attempt to have a more useful quantitative characterization of the energy metabolism of a country, which is based on the various concepts discussed so far, is provided in Fig. 12. The mechanism of accounting suggested here, makes it possible to implement in quantitative terms the different conceptualizations presented in the previous sections in Fig. 1, Fig. 4, Fig. 7, Fig. 8 and Fig. 10. This approach makes it possible to address the distinction between Joules of PES and Joules of EC when assessing the energy consumption of various compartments across hierarchical levels and still keep coherence in the quantitative assessments across hierarchical levels.

Let's start the explanation from the vector on the right part of the top of Fig. 12. This vector is used for the characterization of the metabolism of an element ***i*** (***i*** - indicating any one of the possible sectors or subsectors) of the society can be obtained using 9 pieces of information.

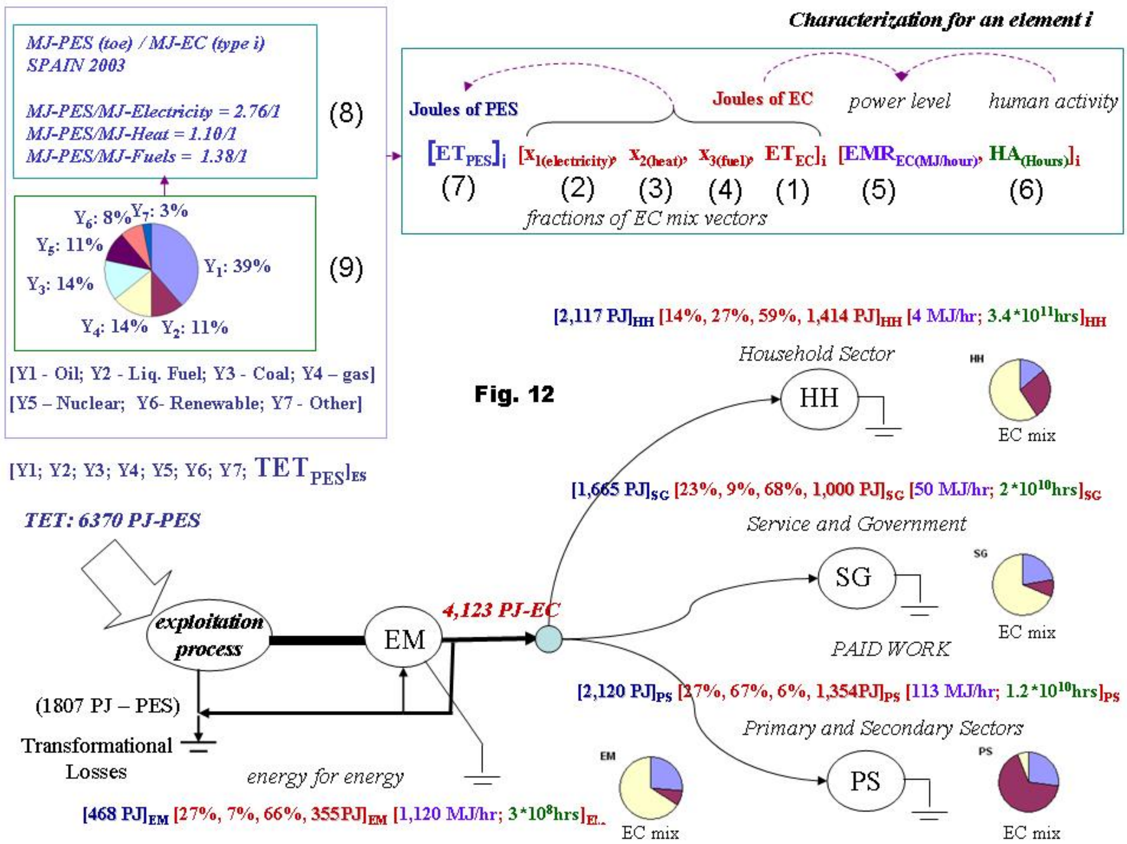


Fig. 12

Starting from the central section (red in the figure) we have 4 pieces of information referring to the energy flowing within each element, which is assessed in terms of Joules of EC:

(1) ET_{ECi} – (Energy Throughput in Energy Carriers) - the consumption of energy of the element ***i***, measured in Joules of Energy Carriers. This number is obtained by summing kWh of electricity, BTUs of heat, and MJ of fuels consumed in the element, after converting the various assessments into a common unit: Joules. No quality factor is used in this assessment;
(2) $x_{1(electricity)}$ – the fraction of ET_{ECi} which is in the form of electricity (measured in Joules over the total measured in Joules);
(3) $x_{2(heat)}$ – the fraction of ET_{ECi} which is in the form of heat (measured in Joules over the total measured in Joules);
(4) $x_{1(fuels)}$ – the fraction of ET_{ECi} which is in the form of fuels (measured in Joules over the total measured in Joules). The sum of the factions of x_1, x_2 and x_3 (making 100%) makes the $ET_{ECi.}$

Moving to the right section (purple and green in the figure) we have 2 pieces of information referring to the power level of this element within the metabolic pattern (Fig. 7 and Fig. 8). As discussed earlier this information makes it possible to deal with the analysis of internal constraints to the viability of a metabolic pattern:
(5) EMR_{ECi} – the **E**nergetic **M**etabolic **R**ate per hour of human activity in the compartment, measured in Joules of Energy Carriers per hour. This number is obtained by dividing the value of ET_{ECi}, by the value of HA_i (hours of human activity in the element ***i***).

(6) HA_i – the hours of **H**uman **A**ctivity allocated in the element ***i*** as resulting from an empirical analysis or a dendrogram of expected allocation of human activity;

Finally on the left section (blue in the figure) we have the last 3 pieces of information, which are required to check the viability in relation to the existence of external constraints:

(7) ET_{PESi} – (Energy Throughput in Primary Energy Soruces) -the consumption of energy of the element ***i***, measured in Joules of Primary Energy Source equivalent. This number is obtained by multiplying the amount of each one of the 3 types of Joules of energy carriers consumed (electricity, heat or fuel) in the chosen element i (Joules of $EC_J = x_J * ET_{ECi}$; with J = 1 → 3) by the losses associated with the generation of each energy carrier (the three conversions MJ-PES/MJ-EC_J illustrated in the conversion factors table (8)).

(8) a table of the conversion losses MJ-PES(toe)/MJ-EC_J specific for the country considered (indicated in the upper left of Fig.12). Thus each one of the carrier types (electricity, heat and fuel) has an associated technical coefficient for its necessary conversion to its Primary Energy Source Equivalent. These values depend on: (i) the technical coefficients related to the generation of energy carriers; (ii) the mix of PES used in the Energy Sector; and (iii) the efficiency of conversion taking place within the specific network installed of a specific country in a certain year.

(9) the mix of PES used in the energy sector to generate the required mix of EC – this mix refer to the specific portfolio of PES adopted by a given society. Also in this case, we can think of a vector [y_1, y_2, . . . y_i, . . ., y_n, TET_{PES}] in which the various fractions of PES used [Fossil types, Nuclear, Renewable types, TET_{PES}] within Total Energy Throughput - TET_{PES} are reported together with the total energy consumption expressed using a given PES of reference ($TET_{PES(TOE)}$).

By adopting this notation, it becomes possible to represent the metabolic pattern of a society in quantitative terms, by combining all the features discussed so far.

* *when dealing with external constraints* – after having decided a particular form of the metabolic pattern from the demand side (setting of socio-demographic variables, functions to be expressed and the technology available), we obtain a definition of a profile of consumption of EC mix in the different compartments together with a specification of an adequate power level. At this point it becomes possible to quantify the resulting external constraints (associated with each one of the PES - y_i - included in the mix) by implementing the analysis illustrated in Fig. 1 and in Fig. 10.

* *when dealing with internal constraints* – after having decided a particular form of the metabolic pattern from the supply side (setting of the constraints coming from the limited capacity of stocks, sinks or the limited availability of land, water, fertile soils, etc) we obtain a definition of possible profiles of supply of EC mix together with a specification of an adequate power level (labor and technical capital requirement in the energy sector). At this point, it becomes possible to quantify and discuss the resulting internal constraints. That is, the possible combinations of final consumption of EC and power levels which can be achieved in the rest of the society (sectors PS, SG and HH), given the congruence constraints over the metabolic pattern – Fig. 4, Fig. 8 and Fig. 10.

The dual profile of allocation of energy consumptions (both in Joules of PES and Joules of EC) across the different compartments of the economy, illustrated on the bottom of Fig. 12 makes it possible to:

(i) compare different countries, both in relation to the consumption in PES and EC of the different compartments (due to either different technology, different mixes of PES or EC, or different relative size of the compartments within the society);
(ii) focus on the study the effect of increases in efficiency and better technology – looking only at the conversion EC → EU;
(iii) focus on the study of the effect of changes in the mix of PES (or import) in the overall efficiency PES → EC → EU.

In fact, it should be noted, that these studies, so far, have been muddled by the difficulty in keeping separated the different causes of losses (the unspecified blending of the losses with the end uses done on the right side of Fig. 11).

4.3 The metabolic pattern of a socio-economic seen from the demand side

The desirability of a given metabolic pattern can be checked starting from a semantic description of the functions, which should be performed by the various compartments of the society (this is the list provided in the right side of Fig. 10). This description should be compatible with the cultural identity of the socio-economic system (this is where a semantic check is required). Then this initial description can be quantified in terms of a definition of internal constraints by mapping the profile of human activity - the profile of hours of human activity over a dendrograms, like done in Fig. 7. That is, this first quantification has to do with demographic variables (dependency ratio) and other socio-economic factors (described in the box in the middle of Fig. 7).

In this way, it is possible to notice that economic development entails establishing a sort of "ratchet effect" on the direction of technical change. The society is continuously adding new functions to be performed by the economy (a more detailed specification of the functions listed on the right side of Fig. 10), which are continuously growing, especially in the service sector, whereas the amount of hours of working time to be allocated in the PS sectors per capita per year tends to continuously shrink. This ratchet effect is due to the fact that the speed at which modern societies learn how to add new functions to the economy is much higher than the speed at which obsolete functions are erased. For this reason, economic development tends to attract an increasing fraction of the total human activity, energy carriers, and technical capital over the functions expressed by HH and SG in the larger loop. This internal competition for critical resources forces a continuous boost in the level of technical capitalization of the primary and secondary sectors. Within the EM and PS sectors the increase in the amount of machine per hour of labor (reflected in a higher EMR measured in MJ/hours), has to compensate the continuous reduction of working hours in these sectors. So far, this stable trend of increase in the power level (EMR) in the primary and secondary sectors has been possible, but only because of the plundering of fossil energy stocks. Finally, for the first time in the history of the oil civilization, the issue of Peak Oil is questioning whether or not, this trend can be maintained.

In conclusion, by looking at the relation "Energy Carriers" → "End Uses" backward, we can establish a relation between a particular metabolic pattern (defined in semantic terms as the set of functions associated with a desirable material standard of living) and the resulting profile of allocation of: (i) energy carriers (with specific mix for each compartments) – determined by the current technology; (ii) hours of human activity – determined by demographic and socio-economic characteristics; (iii) required level of technical capitalization (which can be assessed for the various compartments in terms of the combined value of EMR_i and ET_i). All this information can be handled by using energetic assessment expressed either in Joules of Energy Carriers or Joules of

Primary Energy Sources, but this requires implementing a more complex system of accounting, described in section 4.4.

4.4 The metabolic pattern of a socio-economic seen from the supply side

The current metabolic pattern associated with the expression of the typical structures and functions of modern post-industrial countries depends on the ability of the Primary Sectors to generate an adequate supply of food, mineral and energy carriers for the rest of society, while using a negligible fraction of the available labor (Giampietro and Mayumi, 2000). Moreover, the existing trend in the pattern of growth (associated with the belief that it is possible to have a perpetual economic growth) would require that the Primary Sectors keep increasing their ability to supply the already huge flow of products to the rest of society while further reducing their use of labor. This trend could only be maintained if the Primary Sectors had accessible also in the future natural resources of very high quality – fertile land, rich mineral ores, abundant and easy to extract stocks of fossil energy. That is, when talking of the energy sector in particular, the existing trend of evolution of the metabolic pattern of modern societies depends totally on the availability of high quality PES. For this reason peak oil seems to challenge the widespread belief that in the future it will be possible to keep doing “more of the same”. That is, if modern societies will be forced to exploit PES associated with a much lower output/input energy ratio and a much lower EMR in the energy sector it is doubtful that modern society will be able to maintain the same set of benchmarks described in Fig. 8 and Fig. 9. What if alternative PES in the future will not guarantee a continuous increase in absolute size of the *net supply of energy carriers* to society?

Unfortunately, in relation to these questions, at the moment, the future prospect of alternative PES does not look particularly bright. The quality of the alternative energy sources explored at the moment it is not even close to achieve the benchmarks expected to sustain the metabolic pattern of modern societies. Looking at the internal loop of energy for energy, shown in Fig. 10, we can notice that as soon as we will use alternative PES implying a output/input of EC much lower than the actual 12/1, we should expect either: (i) a dramatic reduction in the amount of Joules of EC consumed in the rest of the society- remaining at the same level of PES consumption; or (ii) a dramatic boost in the environmental impact of modern societies if we want to keep fixed the internal demand of EC in face of a reduction of the output/input of EC in the exploitation of low quality PES. As a matter of fact, the increase in the consumption of EC carriers due to the internal loop of energy for energy will imply a dramatic boost in the pace of consumption of PES, which will result either in an accelerated depletion of stocks and/or increased emission of CO_2, or an overexploitation of renewable resources (overuse of water, deforestation, soil erosion).

Obviously, we are not claiming that it is impossible to find viable alternatives capable of substituting the heavy reliance on fossil Primary Energy Sources. What we want to say, by presenting this analysis, is that it would be wise to perform a *quality check* on the discussion of future energy scenarios, by combining the old wisdom and the recent development in the field of energetics, before investing billions of € and US$ on very dubious alternative energy sources, being well known for their low energy quality – e.g. the biofuel delusion.

Conclusions

1. Energy is a semantic concept, which requires a pre-analytical definition of categories for its quantification – a systematic discussion of this problem at the moment is missing. It is impossible to use a single number - e.g. Joules of total energy consumption of a country - to describe the metabolic pattern of a country, without introducing ambiguity, errors and without missing a number of other important attributes. It would be much wiser develop a multi-purpose grammar - a set of expected semantic relations over energy forms, which can be implemented, in relation to different policy questions, to obtain an integrated set of assessments referring to different attributes (CO_2, water demand, land demand, other wastes, stock depletion, etc.);

2. Socio-economic systems belong to the class of metabolic, autopoietic systems. This simply means that they are making themselves through autocatalytic loops. This implies that they operate through chicken-egg processes, which escape the linear framing and simplification of reductionism. Non-linearity and the existence of non-equivalent representations should be the expected features when we attempt a quantitative analysis of the energetics of the metabolic pattern of these systems.

3. The concepts of "Net Energy Analysis" and "Energy Return On the Investment" (EROI) must be implemented using an integrated set of quantitative assessments:
(i) the overall amount of energy which can be supplied to the society, given the biophysical constraints affecting the exploitation of the relative PES – external constraints both on the supply or the sink side;
(ii) how much energy (expressed in terms of EC) and relative capital, has to be invested by the society within the energy sector in competition with the requirement of the other sectors – internal constraints over competing functions;
(iii) how much working time (expressed in hour of labor) and technical capital has to be invested in the energy sector to deliver the required flow of EC in the rest of the society;

4. The quality and the quantity of alternative PES can only be checked after having defined the characteristics of the metabolic pattern we want to sustain. In turn, on the socio-economic side, this metabolic pattern is related to the feasibility and desirability of the set of structures and functions, which are expected to be expressed by a given society. The set of functions and structures expressed by a society [factors determining the metabolic pattern on the demand side] *do affect* and *are affected by*: (i) the demographic structure; (ii) the structure of the economy (the functions and the relative size of different sectors and sub-sectors), and (iii) the structure of the household sector which can be characterized as a profile of distribution of households over a given typology of household types.

5. We believe that by combining the various theoretical concepts presented in this paper into an integrated framework supported by an appropriate dataset, it would become possible to generate a better informed discussion about future energy scenarios. We believe also that this line of research should be given a certain priority, since many of the current discussions over future energy scenarios seem not to be informed enough.

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