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CAN BIOFUELS REPLACE FOSSIL ENERGY FUELS? A MULTI-SCALE INTEGRATED ANALYSIS BASED ON THE CONCEPT OF SOCIETAL AND ECOSYSTEM METABOLISM: PART 1

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Abstract

Many claim that biofuels represent a viable and desirable alternative to fossil energy fuels. This paper (the first of a series of two) provides a critical appraisal of the claim that a large scale move to biofuels is either feasible or desirable for powering the economy of a developed country. This conclusion is based on an integrated analysis of the performance of biofuels versus that of fossil energy fuels. The text is divided into 2 main sections.

Section 1 provides a semantic framing of the issue. Two metaphors are used to explain why biomass energy was abandoned during the industrial revolution in the first place: (1) the Yin-Yang tension between recycling (to increase ecological compatibility) and linearization (to increase economic competitiveness) of the flows metabolized by society; (2) the energy sector of a society seen like the heart for the human body. An alternative heart, to be viable, must deliver the supply of blood which is expected by the rest of the body both in terms of *quantity* and *quality*. This section concludes that for a developed society not everything that can be burned should be considered as a desirable fuel and it provides a framework for such an evaluation.

Section 2 provides a critical appraisal of the option of biofuels as an alternative to oil. The high labor and land demand per net unit of biofuel delivered to society makes this option not compatible with the typical patterns of metabolism found in developed societies. In relation to ecological compatibility, fossil energy made it possible for the first time in the history of humankind to generate problems on the sink side (accumulation of CO2 in the atmosphere) rather than on the supply side (structural damage to the ecological processes of conversions of solar energy over cycles of nutrients). Agreeing on the fact that humans must find a substitute for fossil energy does not entail that this substitute should be biofuels.

Key-words

Biofuels, fossil energy, alternative energy, societal metabolism, multi-scale integrated analysis, energy analysis, MSIASEM, ecosystem metabolism

1. Introduction

Very often documents and papers suggesting that humans should abandon fossil energy and move to an energy sector powered by biofuels start by saying that “for centuries” or “for millennia”, or “from the dawn of civilization” humans have used biomass for powering their activities. However, this is not a very convincing statement in favor of biofuels. In fact, if we do not want to re-invent the wheel in an era in which people are flying around, when proposing to go back to something which has been abandoned in developed countries - and it is still being abandoned in developing countries, as soon as technical progress moves in - one should explain why the use of biomass as energy source was discarded in the first place. That is, if there is a reason explaining why an energy sector powered by biomass was replaced by an energy sector powered by fossil energy, this reason should be studied to learn what type of problems we could face when moving back to that solution. That is, we should first of all answer the question: are the reasons that led modern economies to the abandonment of an energy sector based on biomass no longer valid?

This paper attempts to answer this question and, more specifically, we will address the issue of the feasibility and desirability of the idea of substituting fossil energy fuels with biofuels. Taking advantage of the opportunity given by the International Journal of Trandisciplinary Research we want to adopt in this paper an approach different from that generally adopted in conventional disciplinary journals. In fact, very often, the conventional scientific approach used to debate sustainability dilemmas entails having the two sides “throwing numbers at each other over the fence” (a very effective expression proposed by Jeroen van der Sluijs). This behavior implies that very often we assist in a “dialogue of the deaf”, in the sense that the numbers which are argued over by the two sides do not mean the same thing within the two proposed systems of accounting or, even worse, they just reflect logically independent analyses referring to different pieces of a bigger picture. This implies that in these debates, when engaged in this “battle over numbers”, each one of the two sides is basically worried about checking the accuracy of their own calculations, which are developed within a particular local definition of the sustainability issue. Very little attention is given to the quality of the narratives adopted before making the calculations.

For this reason, in this paper, we attempt to frame the issue of the feasibility and desirability of the characteristics of a biofuel energy sector operating in a developed society. This is not done by using a formal analytical approach, but by using narratives and metaphors. The main message to be driven home from the first part of this paper is that not everything that can be burned should be considered as an alternative energy fuel for a developed society. In order to decide whether or not “something that can be burned” is a potential input for powering the metabolism of a developed society it is necessary to check the overall compatibility between four key characteristics:

(1) the characteristics of the process generating the supply of the flow of energy carriers used by society both in quantity and quality (e.g. life cycle assessment over the energy sector);

(2) the characteristics of the socio-economic process requiring the given flow of energy carriers both in quantity and quality (e.g. the aggregate requirements of society for its production and consumption of goods and services);

(3) the technical coefficients determining the characteristics of the supply of the flow of energy carriers (e.g. characteristics of the technology and natural resources used within the energy sector);

(4) the characteristics of the ecological processes embedding society and determining admissible boundary conditions for the flows of matter and energy metabolized by society (both on the supply and the sink side).

Section 2 of this paper tries to answer the question "can biofuels replace the actual performance of fossil energy fuels?" using the definition discussed in Section 1 (a more detailed discussion of a methodological approach that can be used to develop the quantitative analysis required for this check is provided in the second paper of this series) . The answer to the question is that: (i) a feasible solution (when assuming that the characteristics of the metabolism of society will have to be dramatically changed to match the constrains determined by the characteristics of an energy sector powered by biofuel) is not be desirable, and (ii) a desirable solution (when assuming that we must keep the actual characteristics of the metabolism of developed societies) is not be feasible.

Finally, the paper concludes that it is time to get out from the stereotypes used to discuss biofuels. In fact, the point that biomass has played a crucial role in making possible and sustainable the metabolism of human societies is certainly relevant. However, it has to be complemented by the consideration that in relation to sustainability biomass performs multiple functions. That is, it does not only supply energy input to human societies, but it also stabilizes those ecological services (through ecosystem metabolism) required for the sustainability of societal metabolism. Actually, the quicker the pace of societal metabolism (the material and energy throughput within the economic process, which is associated with the production and consumption of goods and services for a growing population), the stronger the metabolic activity of those ecosystems which are guaranteeing stable boundary conditions to the relative flows of energy and matter. Biomass will also have to continue to play this same crucial role in the future. Sustainability entails a forced relation, in terms of reciprocal compatibility, over the two metabolisms of ecosystems and societies.

2. Can "everything that burns" be considered a fuel for a developed society?

This section proposes two metaphors which we consider useful for a semantic framing of a discussion over biofuels. The two metaphors are:

(1) the existence of a Yin-Yang tension between internal and external constraints associated with the sustainability of metabolic systems; and

(2) the forced relation between "functional type" and "structural type", when checking the viability and desirability of a heart substitute.

2.1. The Yin-Yang tension associated with the sustainability of metabolic systems

2.1.1 Exploitation of natural resources: relying on cycles versus handling linear flows

A modern environmental problem generated by technological progress is depicted in Fig. 1a. Developed societies are facing a problem of pollution generated by the flow of disposable diapers which is moving too quickly into the garbage sink. Therefore, the problem posed by diapers shares a similarity with that associated with the use of fossil energy fuels. Disposable diapers are very handy at the moment of the use, but they generate too much load on their relative sink. A way to solve this problem would be that of getting back to the use of recyclable diapers. After all, *different forms of recyclable diapers have been used by humankind for centuries or millennia or "from the dawn of civilization"* . . . In fact, looking in the upper part of Fig. 1b we can actually see that recyclable diapers - and even recyclable diapers based on biomass "moss" - were in use in pre-industrial societies within the USA.

Figure 1a. Disposable diapers pose the same problem as fossil energy fuels.

different forms of recyclable diapers have been used since the dawn of humankind . . .

"When moss was used for diapers the baby seldom became chafed, and when it was unwrapped you could smell only sweet moss"

Statement gathered by the ethnologist Imez Hilger in the 1930s from an elder Native American

British Museum

A Tikanagan used by native Americans

So why did humans stop to use recyclable diapers in the first place?

Figure 1b. The problems associated with the use of recyclable diapers.

As noted in the introduction, in order to be able to implement the idea of going back to recyclable diapers we should be able to understand, first of all, why the old fashion recyclable diapers were abandoned in the first place. A quick overview of the problems associated with the use of recyclable diapers is illustrated in the bottom part of Fig. 1b. These problems can be summarized by saying that, in general, human activities dealing with recycling a given output back into the relative input are: (i) labor intensive; (ii) space demanding; (iii) unpleasant; and, in addition to that, (iv) they require energy. Can this statement be generalized? We will do this in the next section, when claiming that the problems with recycling have to do with general principles of thermodynamics. However, before getting into a general discussion of pros and cons of recycling, let us have a look at two other examples relevant for discussing the issue of biofuels.

Example #1 the recycling of "night soil"

The images given in Fig. 2a refer to the application of "night-soil" in a rural area of China. For those that do not know the meaning of this term, "night soil" refers to human excrements that are recycled within the rural community and applied with care (to optimize the efficiency of the process of recycling) to each plant (as illustrated by Fig. 2a). Commenting on these pictures Giampietro (2003, pp 98-99) states that the European agro-ecologists of the team he was working with in China, were delighted by this practice. In fact, an agro-ecologist, especially if coming from a developed country, sees this activity as a key solution to guarantee the sustainability of this typology of farming system (cropping in densely populated areas). On the contrary, when interviewed about their knowledge and practice of environmental-friendly activities, the Chinese farmers claimed that they were not happy at all with handling "night soil". Actually the lady in the picture told Giampietro that the sooner

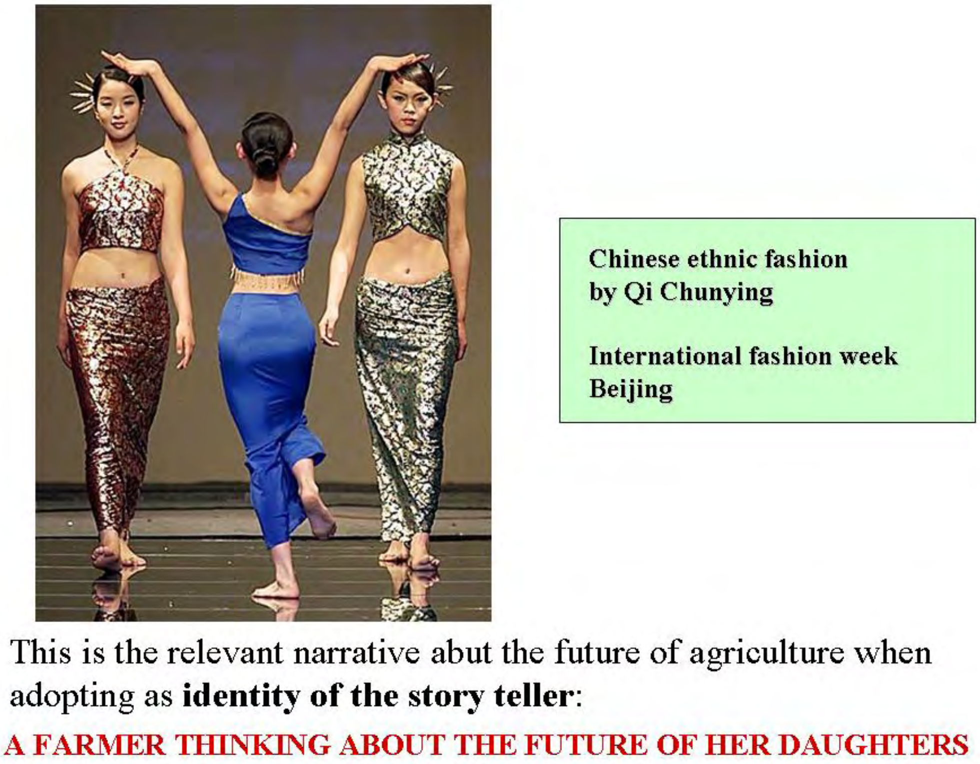
The ultimate wisdom of agro-ecology: the recycling of night-soil:
"Nutrients are going from plants to humans and back to plants . . ."

This is the relevant narrative abut the future of agriculture
when adopting as **identity of the story teller**:

AN AGROECOLOGIST WITH A GOOD SALARY FROM A UNIVERSITY

Figure 2a. The application of "night soil" in rural China.

the farming system she was contributing to sustain would go to hell, the better for her and the villagers. She wanted a better life for her daughters and the daughters of the other villagers (Fig. 2b).



Chinese ethnic fashion
by Qi Chunying

International fashion week
Beijing

This is the relevant narrative abut the future of agriculture when adopting as **identity of the story teller**:

A FARMER THINKING ABOUT THE FUTURE OF HER DAUGHTERS

Figure 2b. International fashion week in Beijing, China.

Example #2 Household biogas plant

Remaining in China, another relevant example of abandonment of environmental-friendly practices is indicated by Vaclav Smil (1988): millions of biogas digestors have been abandoned, as soon as off-farm opportunities and commercial energy have become increasingly available in rural areas. The labor intensive and unpleasant tasks of maintenance of household biogas plants are illustrated in Fig. 3. The pictures there give an idea of the type of activities required for running a biogas digestor, which are happily abandoned whenever this is possible (especially in those areas where the winter is severe). Also in this case, rural people prefer to work in small light industries which provide a more comfortable work situation and higher revenues (both in economic and energetic terms . . .).

Figure 3. The maintenance of household biogas plants.

2.1.2 Metaphor#1: the Yin-Yang tension between cycle and linear flow

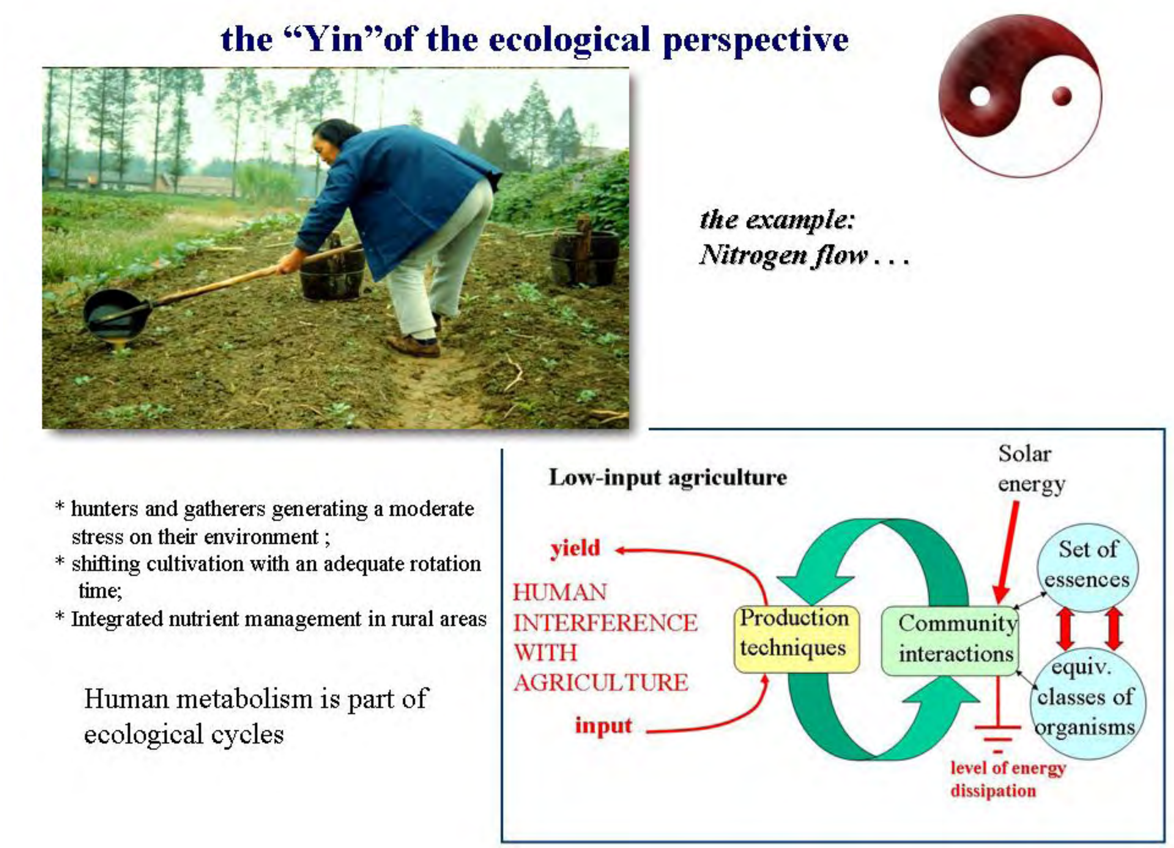
The "pace of the flows used by humans" versus "the pace of the cycles driven by nature"

A key issue associated with sustainability is related to the compatibility between: (1) the pace of the flows of energy and matter used by society in the process of production and consumption of goods and services (what is perceived inside the society when seen as a black box); *versus* (2) the pace of the flows of energy and matter going through the interface society/ecosystem which is embedding the society (what is going in and out the black box from and to its environment). It is well known that in order to have a continuous "flow of something" this "flow of something" has to be recycled. That is, life on this planet is based on bio-geochemical cycles of key elements (e.g. water cycle, nitrogen cycle, carbon cycle), which guarantee the long term sustainability of flows experienced at the local scale, within the various black boxes considered in the analysis. Within these biogeochemical cycles different ecosystems can operate by adapting their local cycles of nutrients – their specific form of metabolism - to the larger cycles determining the stability of their boundary conditions. In the same way, human societies can express their specific form of metabolism, which in order to be sustainable, must be compatible with the boundary conditions determined by the characteristics of the ecosystems embedding them.

Within this framework it is easy to observe that very often the definition of what should be considered a resource or a pollutant depends on the compatibility between the pace of the flows associated with the metabolism of society and the pace of the flows associated with the metabolism of the ecosystem. For example, as illustrated in Fig. 4, the flow of nitrogen associated with the night-soil generated by a small rural village in China is a valuable resource for local agriculture, whereas human excrements generated by a big city represent a pollution problem, which requires capital and running costs to be disposed of.

Figure 4. The flow of nitrogen from night-soil in rural China is valuable, whereas human excrement in an urban center is a pollution problem.

This characterization of the flow as a potential resource or a potential pollutant is obtained when looking at the *external constraints* determining the sustainability of the metabolism of a society. That is, an external constraint is defined when checking the characteristics of the flow generated by the metabolism of society against the constraints imposed by the characteristics of the metabolism of the ecosystem (the view given in Fig. 2a). However, together with external constraints there are also *internal constraints* determining the sustainability of the metabolism of a society. When looking for internal constraints, the pace of the flow of metabolism should be checked against the aspirations of the people living in that society for a better material standard of living (the view given in Fig. 2b). An example of these two different perspectives is given in Fig. 5a, which deals with the pace of metabolism of nitrogen through the agricultural sector. The two pictures illustrate a well known phenomenon in agriculture: in order to keep a high productivity of labor (rich farmers), modern agriculture must rely on linear flows of nutrients, as illustrated Fig. 5b. This requires that massive quantities of nitrogen fertilizers have to be applied per hectare in order to be able to take away massive quantities of crop biomass from the fields per hectare. This solution implies a higher environmental impact (e.g. nitrogen leakages into the water table, stress on the soil, use of pesticides) than the recycling of night soil. On the other hand, in this way, it is possible to stabilize a larger flow of economic added value per hectare (referring to the inputs bought and the crops sold on the market), paid for, by a lower ecological compatibility of high input monoculture. The opposite situation is represented by the "night soil" recycling – Fig. 5a. This solution is much more benign for the soil and the



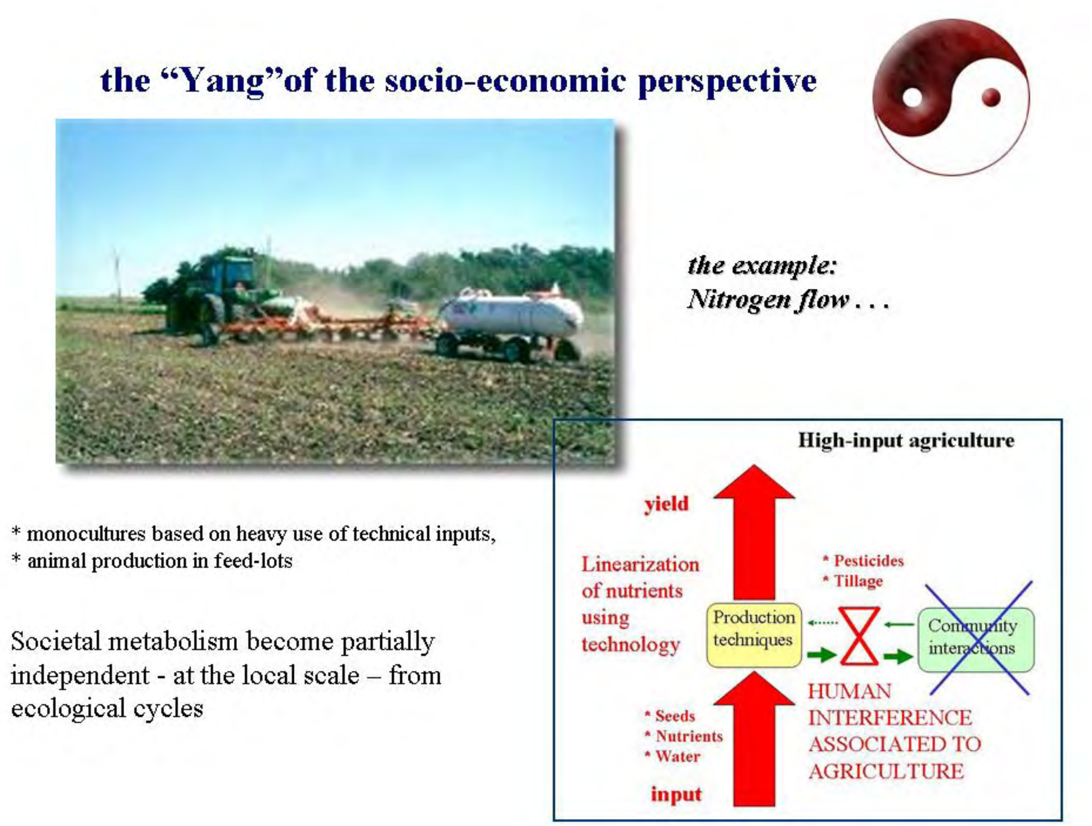
the "Yin"of the ecological perspective

the example:
Nitrogen flow . . .

- * hunters and gatherers generating a moderate stress on their environment ;
- * shifting cultivation with an adequate rotation time;
- * Integrated nutrient management in rural areas

Human metabolism is part of ecological cycles

Figure 5a. The pace of metabolism of nitrogen from night-soil through the agricultural sector.



the "Yang"of the socio-economic perspective

the example:
Nitrogen flow . . .

* monocultures based on heavy use of technical inputs,
* animal production in feed-lots

Societal metabolism become partially independent - at the local scale – from ecological cycles

Figure 5b. Modern agriculture relies on the linear flow of nutrients for farming.

recycling of nutrients, but it implies poor farmers. That is, it generates a density of added value per hectare, which is much lower than the density expected for the categories of colonized land found in developed countries.

We can resume the Yin-Yang predicament of societal metabolism as follows:

* YIN – *Low GDP per capita, matter and energy flows compatible with natural cycles* - When the return of one hour of labor invested in recycling is compatible with the average pace of metabolism of a socio-economic system the impact of the economy on the environment is very low (as long as the population density remain at pre-industrial levels). But the pattern of production and consumption of goods and services must be adapted to the existing ecological limits (no externalization, no imports of resources, no stock depletion, no sink filling).

* YANG – *Large GDP per capita, high opportunity cost of labor* - When the return of one hour of labor invested in recycling is much lower than the return of one hour of labor invested in other activities based on the exploitation of linear flows of matter and energy, recycling implies a cost and therefore it is avoided, since it would imply a lowering in existing material standard of living.

When looking at the issue of sustainability in evolutionary terms, this Yin-Yang metaphor generates a well known paradox.

The dialectic tension between "efficiency" and "adaptability": Jevons' paradox

"*Jevons' paradox (F. Jevons, 1990; Mayumi et al. 1998; Alcott, 2005) was first enunciated by Jevons in his 1865 book The Coal Question (W.S. Jevons, 1865). Briefly it states that an increase in output/input ratio – the "efficiency" in using a resource - leads, in the medium/long term, to an increased use of that resource rather than to a reduction. At that time, Jevons was discussing possible trends of future consumption of coal and reacting to scenarios advocated by technological optimists. In fact, the contemporary of Jevons were urging to dramatically increase the "efficiency" of engines in order to reduce coal consumption. In face of such a claim, Jevons correctly indicated that more efficient engines would have expanded the possible uses of coal for human activities. Therefore increases in efficiency would have boosted the rate of consumption of existing coal reserves rather than reducing it . . . Jevons' paradox has different names and different applications: "rebound effect" in energy literature and "paradox of prevention" in relation to public health. In the latter case, the paradox consists of the fact that the amount of money "saved" by prevention of a few targeted diseases leads to a dramatic increase in the overall bill of the health sector in the long-term.* " (Giampietro and Mayumi, 2006).

Jevons' paradox can be explained, using a thermodynamic reasoning, as generated by two contrasting principles which apply simultaneously to metabolic systems but on different scales: (1) the "Minimum Entropy Production Principle" [(Glansdorff and Prigogine, 1971; Nicolis and Prigogine, 1977)] – the Yin in the metaphor; and (2) Lotka's maximum energy flux (Lotka, 1922) and/or Odum's maximum power principle (Odum and Pinkerton, 1955, elaborated further in Odum, 1996) – the Yang in the metaphor. A discussion of this paradox (which is very relevant for the discussion about biofuels) is given in Giampietro and Mayumi, 2006. A discussion of the thermodynamic implications of Jevons' paradox is available in Giampietro and Mayumi, 2004; Mayumi and Giampietro, 2004. Jevons' paradox points at the existence of an internal tension associated with the issue of sustainability for metabolic systems. A higher pace of dissipation (the Yang) entails the ability to do more - e.g. producing and consuming more goods and services - and therefore it implies the ability of expressing more complexity of behaviors and possible controls, that is, more competitiveness. On the other hand, this entails destroying favorable gradients available at a faster pace, putting more stress on the environment. The other solution, a lower pace of dissipation (the Yin) makes the system weaker against competitors powered by a more vigorous metabolic process. On the other hand, this entails reducing as much as possible the stress on the environment. When facing this dilemma, it is impossible to define, in substantive way, an optimal solution between the two goals of being more powerful or more environmentally benign (Giampietro, 2003 – Chapter 3). As illustrated by life, evolution is associated with a mix of strategies adopted by different typologies of dissipative systems ("small is beautiful" versus "bigger is better").

The relevant issue here is that when dealing with the energy conversions taking place within a society – that is, with the metabolism of an adaptive system and its sustainability - it is not wise to rely only on a local and simple definition of quality for an energy conversion. For example, if the output/input of a process producing biofuel is higher than 1, then this solution is desirable. When dealing with sustainability the efficiency of a conversion is only a part of the story. Another crucial characteristic is always the power level at which useful energy is generated and applied by society. Unfortunately, assessing the power level at which a society is operating (the power density of useful energy) is an elusive "task" since it entails assessing at the same time: (i) how the power is generated (from the inside of the black box); and (ii) how the power is applied in interacting with the environment (from the outside of the black box). These two representations are non-equivalent since they refer to different scales and therefore cannot be handled within conventional formal analysis - for more on this point see Giampietro and Mayumi (2004). In spite of this complication, it is crucial to have a good understanding of the fact that the level of power (the pace of local throughputs) at which a given society is operating is crucial and it is associated with the identity of that society. This is why we propose that the characterization of an energy sector has always to be done by considering: (1) the total amount of throughput required (an extensive variable); (2) the pace of the throughput (the power level); and (3) the output/input ratio (making it possible to check the load on the environment). A higher power level tends to be associated to a lower output/input ratio (Odum and Pinkerton, 1955) - e.g. the faster you drive, the lower the mileage of your car. On the other hand, when the output/input is too small, we can get an aggregate requirement of input from the environment that can exceed its capability of supply. The power level is therefore a crucial piece of information, since we cannot compare the performance of a truck to that of a small motorbike on the basis of the information relative only to their energy conversions. Big trucks and small motorbikes are different and have a different performance. After admitting that there is a trade-off between efficiency and power, it is impossible to discuss the desirability of a process of energy conversion or the desirability of a given energy converter without first contextualizing its requirement of power level. This issue is addressed in the next section using the metaphor of the heart.

2.2 The viability and desirability of a heart substitute

The second metaphor that we want to use for framing the issue of the feasibility and desirability of biofuels as a potential substitute of fossil energy fuel is illustrated in Fig. 6. This metaphor is based on the peculiar characteristic of the organization of metabolic systems. As suggested by the seminal work of Prigogine's school (Prigogine, 1978; Prigogine and Stengers, 1981), human societies and ecosystems both belong to the class of dissipative systems. These systems are able to maintain their own identity because of a continuous process of metabolism, which requires the ability to: (a) stabilize a coordinated inflow of matter and energy resources; and (b) dispose of the flow of degraded matter and energy flows to their context. Living systems have an additional peculiar characteristic. Not only can they generate a predictable pattern of dissipation, but they use their metabolic inputs – e.g. food, fossil energy and useful materials for human societies; solar radiation, nutrients and water for terrestrial ecosystems - to express semiotic activity. That is, living systems are capable of learning how to better interact with their environment while producing themselves - e.g. through reproduction, gathering of data and running anticipatory models about themselves interacting with their context (Maturana and Varela; 1980; Rosen; 1985; 2000; Pattee, 1996; Giampietro et al. 2006a). Because of this they are learning and adapting in time continuously updating their identity in time.

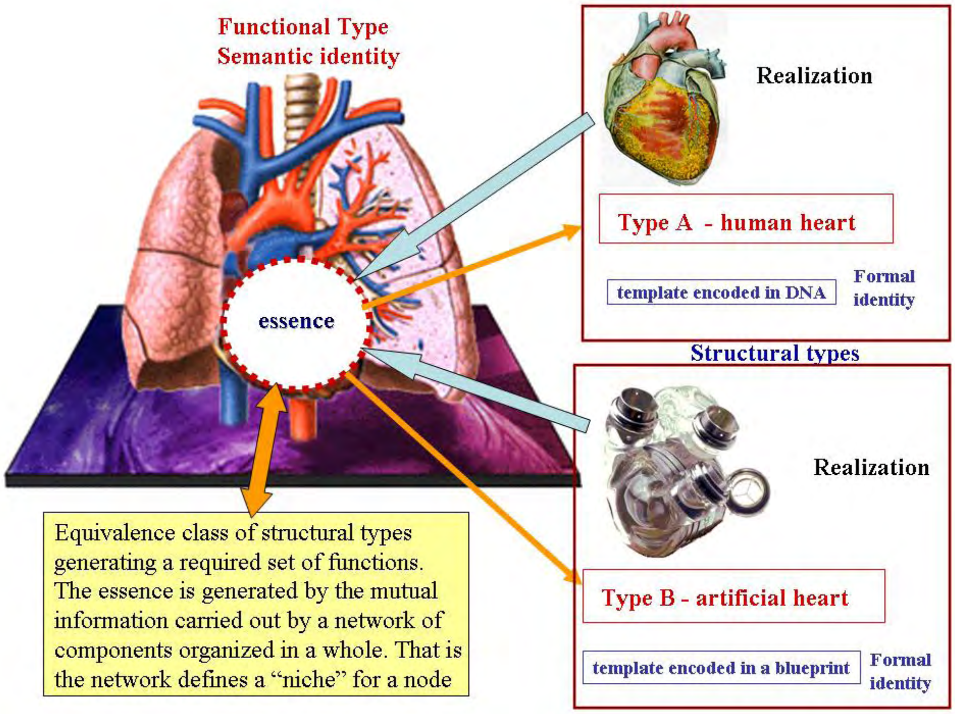


Figure 6. The heart can be used as a metaphor for human societies and ecosystems.

The metabolism of complex adaptive systems such as ecosystems and human societies is based on a network of energy forms controlling each-other via a series of positive and negative feed-backs able to modulate the occurrence of autocatalytic loops (Odum, 1983; Ulanowicz, 1986; 1997). This entails that the various elements making up these networks express characteristics which can be expected by them, since they are associated with their encoded identity used in reproduction. For example, the metabolism of a cow, a liver of a human being, a car, a developed city, can be studied in terms of expected patterns. In turn, this implies that different elements of these networks, operating on different scales, express their typology of metabolism– e.g. cells making up organs, organs, individual human beings, households, villages and whole countries – which has to be defined and characterized in non-equivalent ways (Giampietro, 2003). In any case, this hierarchical structure generates a strong constraint on the compatibility of the characteristics of the various elements – which are performing different roles at different hierarchical levels – within the same organic whole (Ulanowicz, 1986; Pattee, 1996, 2000; Giampietro, 2003).

To simplify such a technical discussion we illustrate in Fig. 6 a key concept associated with the nature of dissipative networks. Metabolic systems operating across multiple levels and scales must be able to establish a forced correspondence between a functional type and a structural type. The main point made by the figure is that when dealing with "*an element*" of a network interacting with "*the rest of the network*" we can define in two non-equivalent ways the characteristics of that element. In the example of Fig. 6 the *element* is the heart of a human being and the *rest of the network* is the circulatory system operating in the rest of the body.

Definition #1 – from outside the black-box - the functional type of a heart. It represents the behavior expected "from that element" by the rest of the network to which the element belongs. That is, there is an image of the heart, associated with the mutual information carried out by the various elements making up the network, which is referring to the interface between two hierarchical levels (the level *n* = the whole heart; and level *n+1* = the network of the rest of the body to which the heart belongs as a part). This is the functional type determining the functional characteristics defining an "expected performance" - so to speak - of the rest of the body from a pulsing heart. The definition of a functional type defines an equivalence class of structural types of pulsing heart, which can be transplanted into the given body with the goal of keeping it alive.

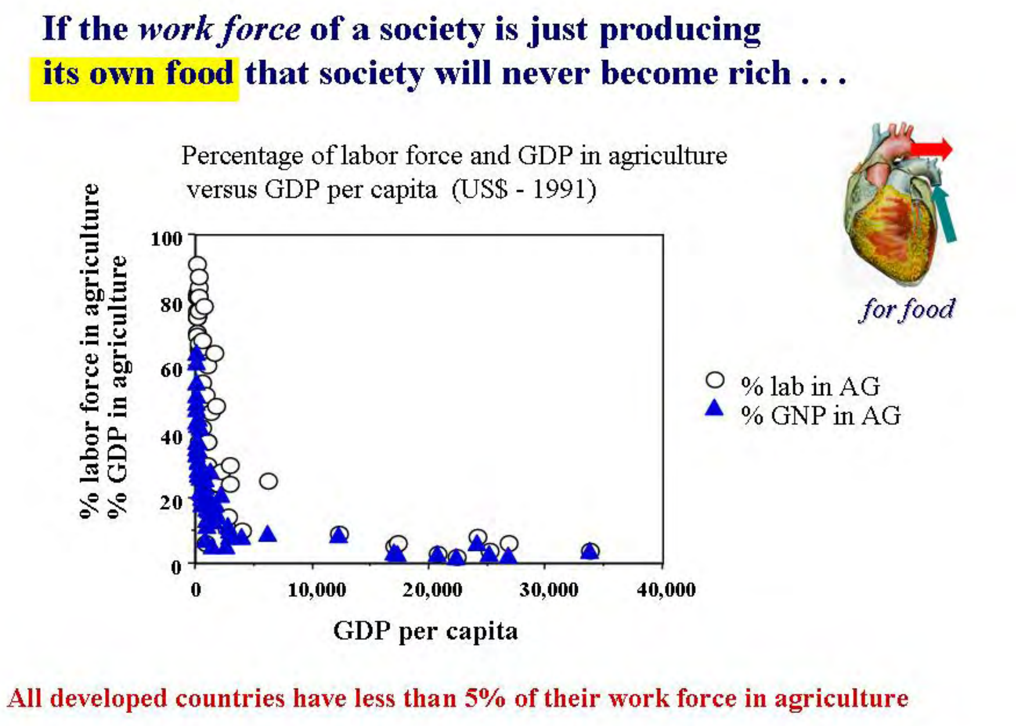
Definition #2 – from inside the black-box – the physical realization of a structural type. It represents an organized structure which has been generated by a physical process of fabrication which map onto a given template. Such a structural type refers to the interface between two hierarchical levels (level *n* = the whole heart; and level *n-1* = the components of the heart, which are assembled in a particular way to generate the whole).

According to these two definitions a successful heart transplant can be done either by: (i) replacing a given realization with another realization of the same structural type (e.g. moving a functioning human heart from a body to another); or (ii) replacing a given realization of the structural type - a human heart - with a realization of a different structural type - a mechanical heart, capable of performing the required function (Fig. 6).

A more detailed discussion of the theoretical implications of the forced coupling of functional and structural types (the concept of holons and holarchies introduced by Koestler) and the link with network analysis is available in Giampietro (2003, chapter 8) and Giampietro et al. 2006a. A discussion of the heart metaphor in relation to the integrated analysis of alternative energy sources is given in Giampietro and Ulgiati, (2005), from which the following quote is taken: "*Returning to energy sectors and societal exosomatic metabolism, the definition of functional type referring to the expected function from the network (e.g. what a society expects from an energy sector) makes it possible to discuss whether or not a given structural type (e.g. an energy sector based on biofuel) is feasible −does it match the expected set of requirements?− and whether or not it is desirable −is it doing better or worse than the structural type it is replacing (e.g. the energy sector powered by fossil energy)? In conclusion, when dealing with a metabolic system (a complex dissipative network organized on multiple levels and scales) it is possible to characterize not only the feasibility, but also the desirability of an element of the whole. When dealing with the situation illustrated in Figure 6, the issue is not whether it is possible to produce an artificial pump that fits into the assigned size (in the metaphor if there is enough land to produce biofuel) and that manages to generate a positive flow of blood (in the metaphor if the energy output/input ratio of the process generating biofuels is greater than 1). But rather, can the pump of the artificial heart (in the metaphor an energy sector based on biofuels) provide a certain level of blood pressure that matches the requirement of the circulatory system (a performance similar to that provided now by an energy sector based on fossil energy)?*". As discussed earlier, such a check should consider the level of power of the supply of energy input to society.

2.2.1 Does this imply the existence of a socio-economic constraint determining a threshold of power level in the supply of energy to society for the energy sector?

The metaphor of the heart can also be used to study the trend in changes of power level in the supply of food which took place in the agricultural sector of developed societies. The agricultural sector is in charge for guaranteeing the metabolism of endosomatic energy. In fact, according to the definition introduced by Lotka (1956) and elaborated by Georgescu-Roegen (1975), social systems have two different forms of metabolism: (1) an endosomatic metabolism - food can be seen as endosomatic energy input (metabolized internally to the human body) by society; and (2) an exosomatic metabolism – this includes all other energy sources powering human activity with energy conversions occurring outside the human body. From this perspective the agricultural sector and the energy sector should be considered as the two sectors in charge for guaranteeing an adequate supply of inputs in relation to these two forms of metabolism. When looking at an international comparison of the power level achieved in food production by the agricultural sectors of different countries – Fig. 7 – it is possible to observe that all the countries in the world that have a GDP per capita higher than 15,000 US$ per capita per year, have a fraction of the work force in agriculture which is below the level of 5% (Giampietro, 1997a). That is, if a society is investing a large fraction of its available supply of working time, just in producing its own food, it will never become rich. In this way, it cannot diversify the set of activities performed by its economy.



If the *work force* of a society is just producing its own food that society will never become rich . . .

All developed countries have less than 5% of their work force in agriculture

Figure 7. A comparison of the power level achieved in food production by the agricultural sectors of all developed countries.

Does the same socio-economic constraint apply to the characteristics of the energy sector which is guaranteeing the metabolism of exosomatic energy? The quick answer to this question is yes. In developed countries the energy sector is absorbing even less work time than the agricultural sector. That is, less than 1% of the work force is absorbed by the energy sector of a developed society in spite of the huge amount of energy consumed per capita in these societies. A more elaborated discussion of this point is given in the next section.

2.2.2 Can we quantify the socio-economic constraints on the power level of the supply?

When adopting the concept of societal metabolism, can we define a threshold of "power level requirement" for the flow of energy input supplied by the energy sector to a given society? To make a long story short (Giampietro, 1997b, 2000, 2001, 2003; Giampietro et al., 1997), the answer is yes and the basic approach for doing so is illustrated in Fig. 8a and Fig. 8b.

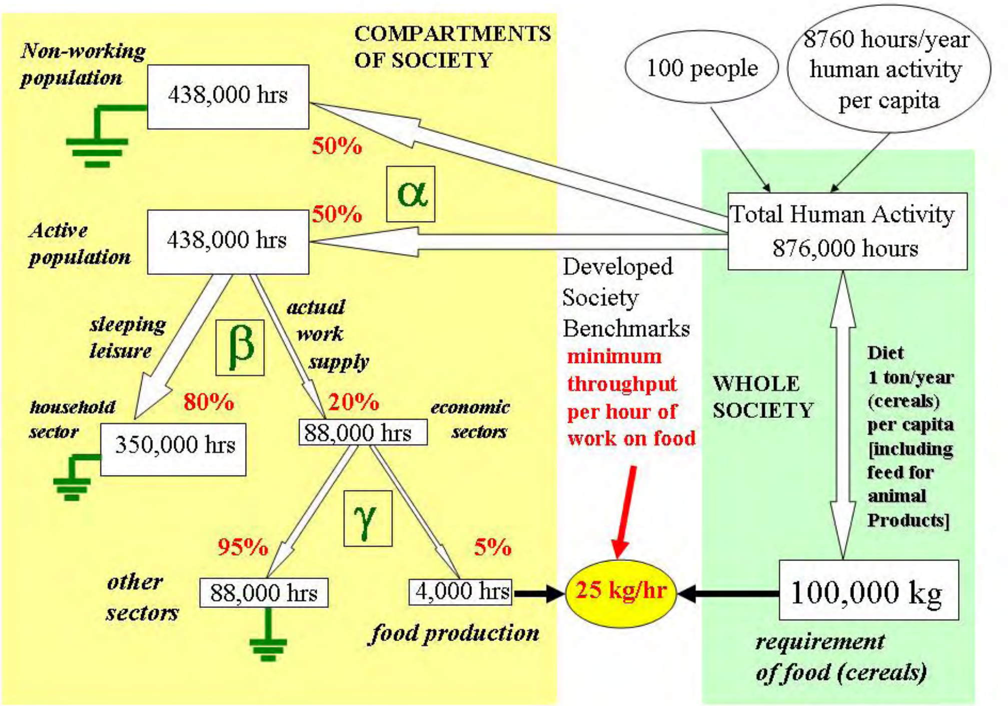


Figure 8a. The flow of endosomatic energy input from the agricultural sector to society must be increased to provide an adequate supply to the rest of society.

Let us start again with the analysis of the endosomatic metabolism which is easier to follow. The scheme in Fig. 8a deals with the characterization of how much the flow of endosomatic energy input to society (in this case cereals) has to be boosted, within the agricultural sector, in order to provide an adequate supply to the rest of society. This analysis is referring, in generic terms, to 100 people living in a developed country. These 100 persons, over a year, will generate 876,000 hours of human activity. Using a set of characteristics describing the diet, as well as the demographic structure and social rules typical of a developed country, we can make the following characterization of the metabolic flows: (1) at the *level n*, that is, within the box on the right in Fig. 8a, we can express the overall flow using average values referring to the whole. That is, the amount of total human activity (expressed in hours) available at the level of the whole society is divided by the total amount of cereals consumed. This provides a pace of metabolism per hour which refers to the *level n*; (2) at the *level n-1*, that is, within the box on the left in Fig. 8a, the whole of total human activity breaks down in different societal compartments, which are measured in terms of hours of human activity invested in different categories of activities. They are defined according to the following splits:

* α - out of the total available human activity (876,000 hours) only 50% of it is potentially available for work, due to the dependency ratio (demographic structure).

* β - the potential human activity expressed by the active population (438,000 hours), is reduced by 80% by the required investments in sleeping, leisure and personal care (physiological overhead on the human activity of adults).

In conclusion, when considering α and β together, they translate into a meager 10% of the total initially available human activity (88,000 hours) which can be invested, at the societal level, in work supply. This means that in a modern society, looking at the profile of investments of human activity, there is only 1 hour of work invested in the economic sectors producing goods and services out of 10 hours spent in activities associated with consumption.

***** γ - the share of work force allocated to agriculture, is below 5% in all developed countries. This is an additional characteristic of modern societies to be considered when coming to the last reduction indicated in Fig. 8a. Modern societies are very complex and this translates into a huge variety of goods and services produced and consumed, which, in turn, requires a huge variety of sectors of activity, jobs descriptions and different typologies of expertise (Tainter, 1988). This implies that the endowment of hours of work supply available for a given developed society tend to be spread as evenly as possible over different sectors and tasks (with service and government sector getting more and more a bigger share). In a developed country it is unthinkable to have 60% of the workforce in agriculture. As illustrated in Fig. 7 the process of industrialization and post-industrialization of modern economies is based on the dramatic reduction of the fraction of the work force allocated in agriculture. If we account for all the previous reductions (α and β) and this additional splitting over competing activities, we are left with a negligible fraction of the total human activity which can be dedicated to food production (in our example not even the 0.5% of total human activity) – 4,000 hours. Please note that in the USA this value would be even lower, since only 2% of the work force (0.2% of total human activity) is in agriculture.

In conclusion, in our hypothetical society, which reflects the standard characteristics of a modern society, all the food consumed in one year by a single person has to be produced with less than 40 hours of work (less than 20 in the USA). The alternative is to be dependent on imports to fill the gap, a solution that no developed country likes for security reason. This entails that given an average level of food consumption per hour of human activity for the whole society, there is a biophysical constraint on the pace (the power level per hour of human activity invested there) at which food must be produced in the agricultural sector. In the example illustrated in Fig. 8a there is a minimum threshold for the productivity of labor in food production which is indicated in 25 kg/hour of work. In reality the throughput of kg of cereals per hour of labor in agriculture is much higher (in the order of hundreds of kg per hour), since farmers have to perform many other tasks besides producing cereals. In any case, this means that if the hypothetical developed society would adopt a technique of food production with a labor productivity of 2 kg/hour of labor (a value typical of pre-industrial subsistence societies in rain-fed agriculture) it would be impossible to sustain: (1) the level of consumption indicated in this example (i.e. 1 ton of cereal per year, which is the actual level of consumption of US citizens when including the cereals directly consumed in the diet, and those used for animal products and beer production); and/or (2) the socioeconomic characteristics associated with the values of α, β, and γ - i.e. life span determining the dependency ratio, work loads per year, and level of services in the economy.

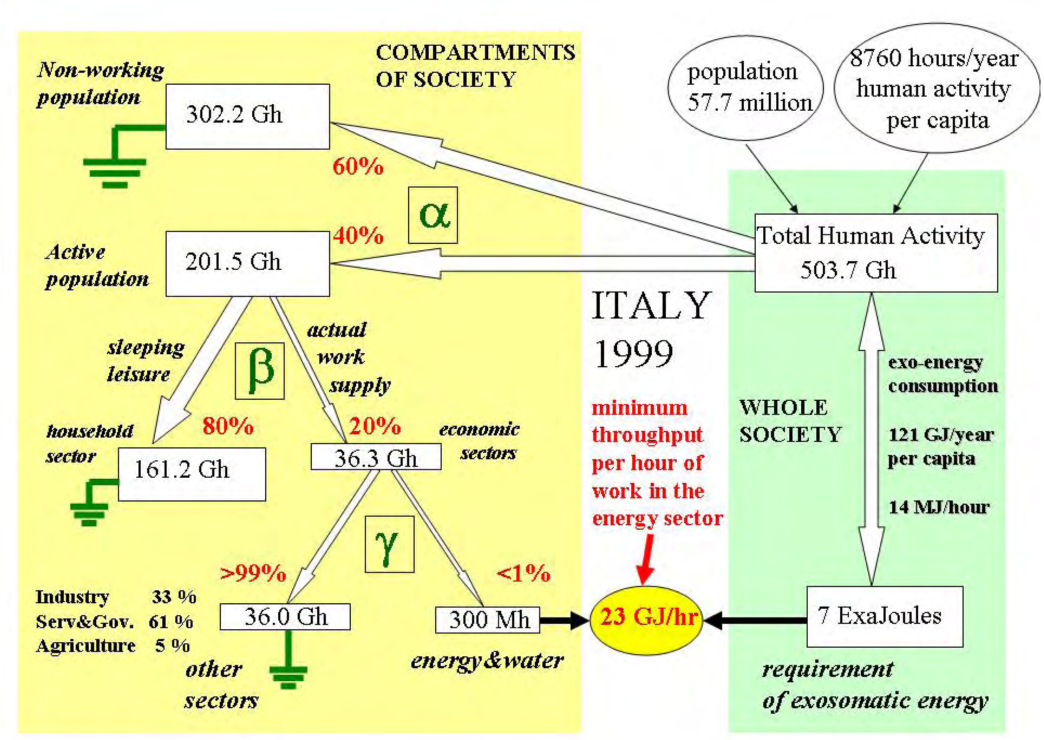


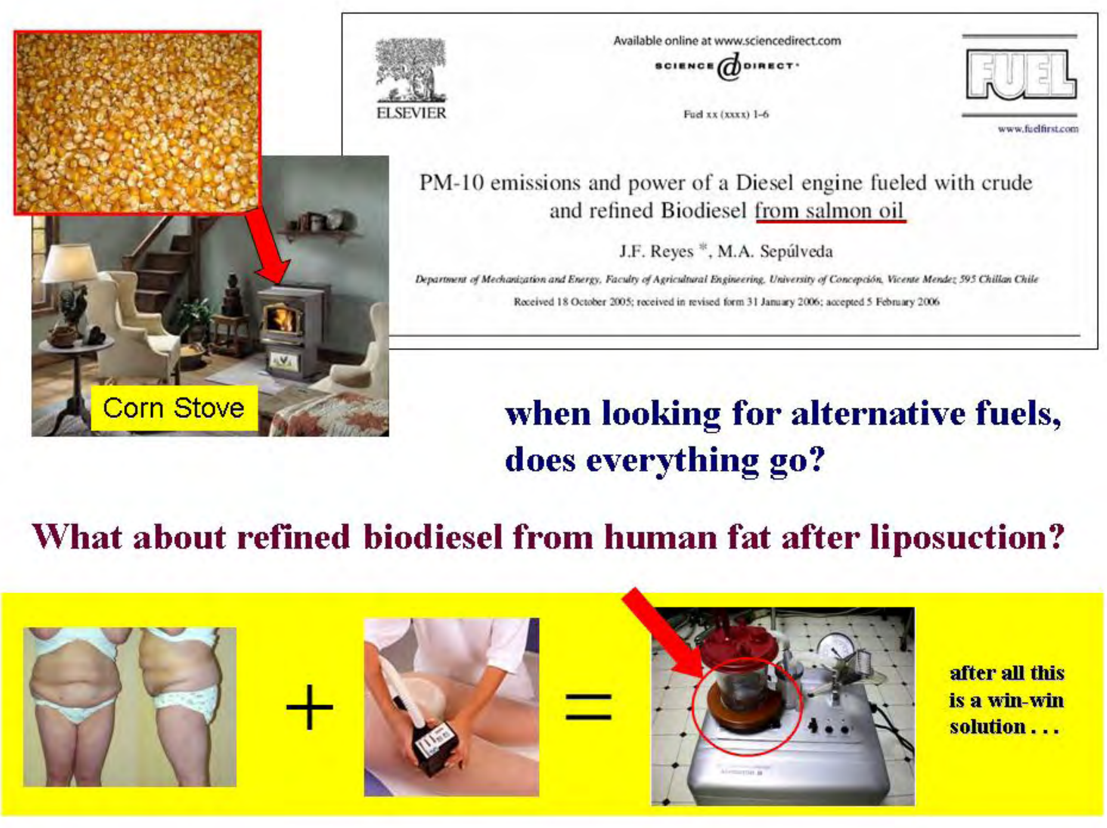
Figure 8b. Exosomatic energy in the energy sector of Italy in 1999.

The same type of analysis can be applied to the metabolism of exosomatic energy of modern societies. An example of such an analysis is given in Fig. 8b. In this example, we use real data referring to Italy in 1999. This to show the power of this approach that can be applied either to "typologies" of countries using benchmark values, or to real countries with empirical data, enabling the validation of hypotheses. The set of values α, β, and γ, characteristic of Italy are given in the figure. Note that Italy had in 1999 a per capita energy consumption of 14 MJ/hour (or 120 GJ/year) which is below the range of values found for other developed countries (30 – 40 MJ/hour or 250 – 350 GJ/year per capita). On the other hand, Italy's population structure implies a dependency ratio of 60%, which is higher than that of other developed society, such as the USA or Australia (about 50%), because of the high percentage of elderly in Italian population. Current demographic trends indicate that in a few decades this pattern may be followed by most developed countries. The value of exosomatic power density per hour of human labor in the energy sector in Italy, in 1999, was 23 GJ/hour. The implications of this benchmark value, in relation to the performance of biofuel production will be discussed in Section 2.

2.3 How to check the feasibility and desirability of alternative fuels

2.3.1 When looking for alternative fuels "does everything go"?

When looking at the growing literature on biofuels, and to the many initiatives aimed at supporting the research for alternative energy sources, we can find an amazing diversity of options which are proposed for escaping current dependence on fossil energy. As illustrated in Fig. 9a these solutions can include stoves running on corn (that suggests the idea of replacing coal with corn), or biodiesel produced from salmon-oil (that suggests that idea of replacing fossil energy fuel with salmon fat). To stigmatize this trend toward the study of solutions which are getting more and more bizarre, Giampietro decided to "make-up" yet a new possible alternative source: "biodiesel from human fat", which could be obtained as a by-product of liposuction (bottom part of Fig. 9a). However, after preparing the slide in the lower part of Fig. 9a Giampietro was told that this idea has been already implemented for real in New Zealand (see the material presented in Fig. 9b to believe it).



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PM-10 emissions and power of a Diesel engine fueled with crude and refined Biodiesel from salmon oil

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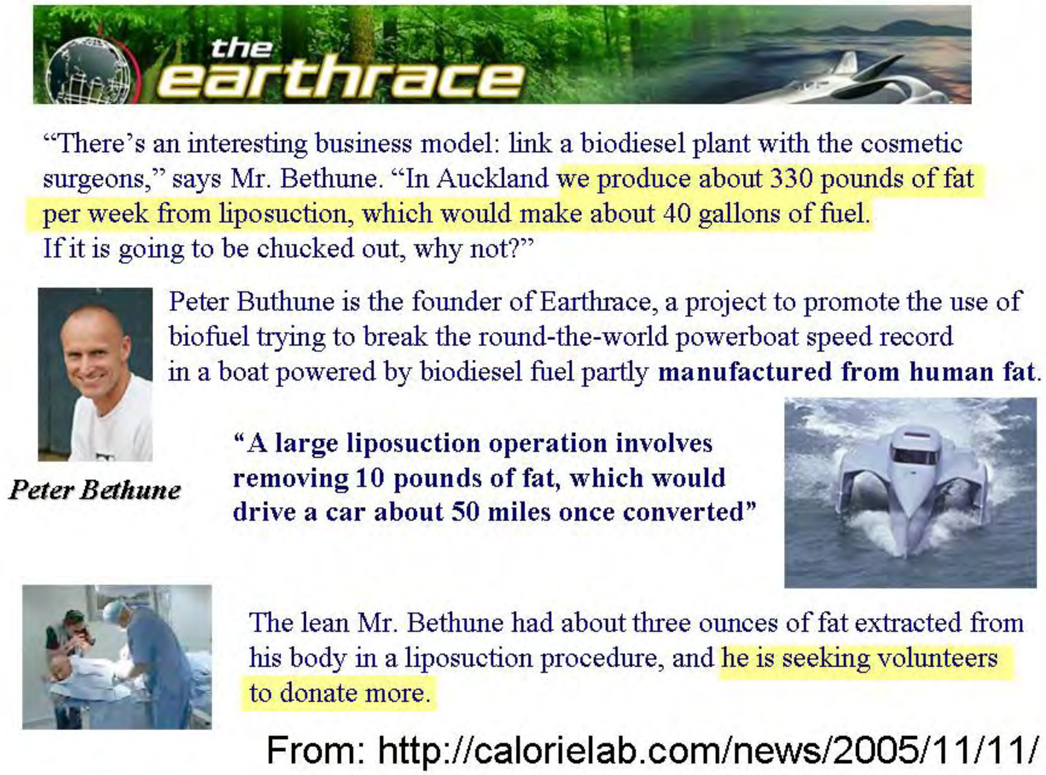
when looking for alternative fuels, does everything go?

What about refined biodiesel from human fat after liposuction?

after all this is a win-win solution . . .

Figure 9a. Various examples of what can be used for alternative fuels.



"There's an interesting business model: link a biodiesel plant with the cosmetic surgeons," says Mr. Bethune. "In Auckland we produce about 330 pounds of fat per week from liposuction, which would make about 40 gallons of fuel. If it is going to be chucked out, why not?"

Peter Buthune is the founder of Earthrace, a project to promote the use of biofuel trying to break the round-the-world powerboat speed record in a boat powered by biodiesel fuel partly **manufactured from human fat**.

Peter Bethune

"A large liposuction operation involves removing 10 pounds of fat, which would drive a car about 50 miles once converted"

The lean Mr. Bethune had about three ounces of fat extracted from his body in a liposuction procedure, and he is seeking volunteers to donate more.

From: http://calorielab.com/news/2005/11/11/

Figure 9b. The use of human fat as biofuel in New Zealand.

This proliferation of possible alternative energy sources proposed to get developed societies out from the current "addiction to oil" generates the problem of how to evaluate priorities for research. In fact, not everything that can be burned should be considered as a potential energy source for powering a developed society. When looking at the body of knowledge expressed in the traditional school of energy analysis it is clear that different energy sources do have different quality: not everything goes. There are different approaches that have been proposed for addressing this issue - e.g. EMergy analysis developed by the Odum school (Odum, 1983; 1996), the EROI (Energy Return on the Investment), expressly developed for energy sources by Cleveland et al. (1984); (2000); Hall et al. (1986); There is also an Exergy analysis (Ayres et al. 1996; 2003; Szargut et al. 1988) originally developed for a technical process and lately has also applied to the metabolism of whole societies. Put in another way, it is important to be aware of the stigmatization used by Samuel Brody (1945) in the last chapter of his masterpiece on power analysis of US agriculture. To those proposing to power the mechanization of the US agricultural sector with ethanol from corn he reminded them of the famous quote attributed to Marie Antoinette: "if the people have no bread, then let them eat the cake . . ."

2.3.2 The quality check on large scale scenarios

To be considered as an alternative to fossil energy an energy source has to pass a multi-criteria screening. That is, the overall evaluation of its feasibility and desirability should not refer only to the calculation referring to a unit of mass of the suggested fuel (e.g. how many

MJ of fuel can be derived from a kg of human fat obtained from liposuction) or to the overall output/input energy ratio (e.g. if the process of generation of energy carriers provides more energy than it consumes). Rather it is essential to check the ability of the whole energy sector to match both in quantity and quality the constraints associated with the characteristics of: (i) the metabolism of its socio-economic context; and (ii) the metabolism of the ecosystems guaranteeing the long term sustainability to the societal metabolism.

That is, a sound evaluation of potential alternative fuels has to be based on a Multi-Scale Integrated Analysis having the goal to check the compatibility between 4 key pieces of information:

1. characteristics of the whole process generating the supply of fuel (energy sector);
2. characteristics of the process requiring such a supply (the structure of the mix of requirements from the other sectors including the profile of allocation of human activity over the various socio-economic compartments);
3. biophysical constraints associated with the technical coefficients (the conversions in the energy sector, quality of energy sources analyzed over the whole life cycle);
4. biophysical constraints determined by the need of preserving ecological integrity (acceptable levels of environmental loading).

3. Can biofuels replace fossil energy fuels?: a reality check

3.1 The Achille's heel of biofuels

3.1.1 The internal loop in production

As discussed in Giampietro et al. (1997a), Ulgiati (2001) and Giampietro and Ulgiati (2005) when dealing with scenarios in which biofuels will represent a significant source of energy carriers for society, there is a major problem which is associated with key characteristics of their process of production. "*The*" problem is represented by the internal loop of energy requirement. Looking at the scheme of accounting given in Fig. 10, the constraint on the feasibility of the overall process can be written as:

$$\text{output/input} > 1 = F1 > (F2 + F3 + F4)$$

where F1 is the amount of biofuel output generated in the production process and F2, F3, and F4 are the different energy inputs required/consumed by the process of biofuel production in the form of fuel energy. This internal loop implies an important non-linearity which is experienced even with small variations of the value of the overall output/input. This non-linearity can be briefly illustrated by the following two examples:

A: output/input energy ratio $F1/(F2 + F3 + F4) = 1.5$
net/gross output of biofuel $(F^*/F1) = 0.33$
net supply (F^*) of 1 liter of biofuel entails the gross production ($F1$) of 3 liters of biofuel.

B: output/input energy ratio F1/(F2 + F3 + F4) = 1.2
net/gross output of biofuel (F*/F1) = 0.16
net supply (F*) of 1 liter of biofuel entails the gross production (F1) of 6 liters of biofuel.

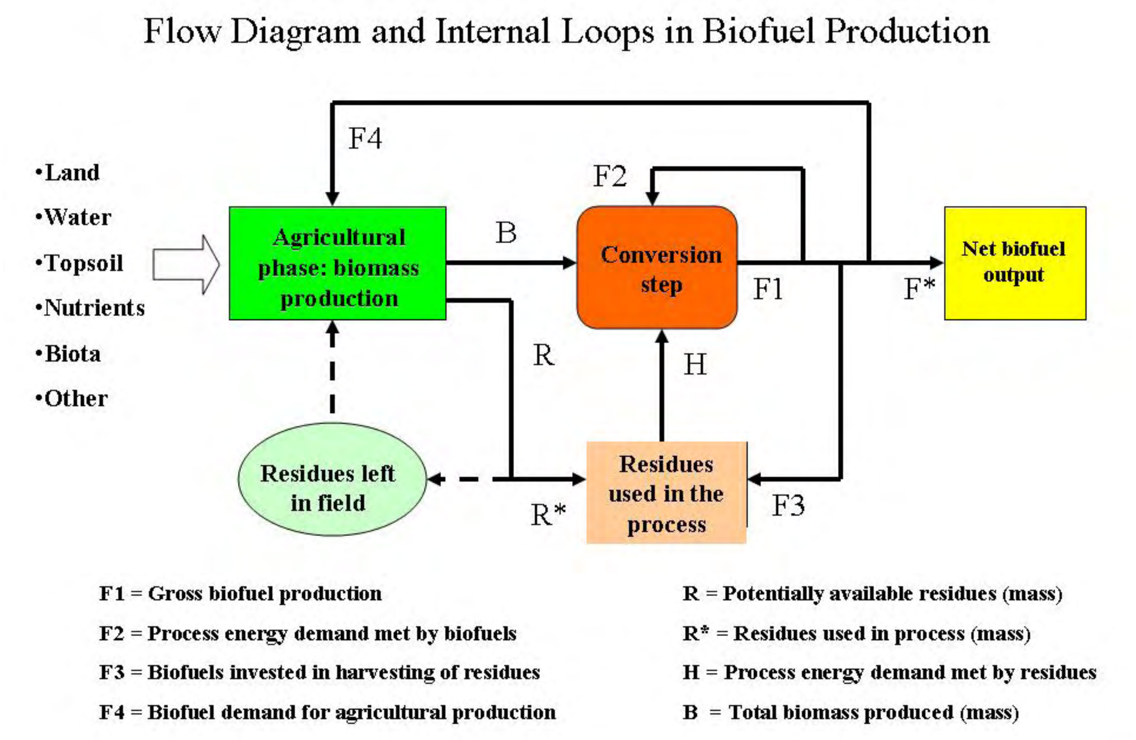


Figure 10. A flow diagram and internal loops in biofuel production.

That is, when the output/input is low, a reduction of 20% in the output/input energy ratio, from 1.5 to 1.2, doubles the energy consumption of the energy sector (within the energy consumption of society) and this further boosts the already high ratio (3/1) of gross to net production. This in turn will boost the relative demand of land, water and labor associated with the gross production of biofuel.

This is a major problem that seems to be systematically ignored by those providing an optimistic analysis of biofuel production. This problem translates into the need for complicated and high-tech processes of production aimed at getting the maximum in efficiency for the output/input energy ratio. However, this is a solution which is not good for flexibility. It is well known that an excessive attention for efficiency translates into brittleness for the system of production (which becomes fragile in case of perturbations) and into more environmental impact. In fact, the need for extremely high yield in the production of inputs drives towards monocultures and towards linearization of flows. The need for a very high output/input drives toward reduced used of fertilizers (e.g. in sugar cane production) and for a complicated network of re-use of input (requiring big infrastructures or additional labor).

3.1.2 The issue of scale: when producing biofuels what should be considered as an output?

In the scientific literature there is a debate on whether or not the production of ethanol from crops (e.g. corn) has an output/input higher than 1. Just to provide a recent example of this debate we refer to the quarrel between Shapouri et al. (2004) reporting a positive return of 67% for net energy, and Pimentel and Patzek, (2005) reporting a negative 43% deficit.

A small fraction of this discrepancy can be explained by: (i) different choices done by the different authors when making the calculations – e.g. Shapouri et al. (2004) included in their analysis only the yield of the best nine states of USA, whereas Pimentel and Patzek used average yields at the national level (USA); and (ii) minor differences in the accounting of the inputs to the process and their energy equivalence. However, the main factor generating contrasting numbers about output/input ratios for ethanol production from biomass is related to the decision on how to deal with the accounting of the by-products of such a process - primarily dried-distillers grain (DDG) that can be used to feed cattle. Those supporting the option of biofuel adopt a very creative system of accounting to this regard. They consider DDG as an output of the process of production of biofuels, which is true. But they account for this output as a net supply of fuel measured in MJ of oil equivalent (like if they were a high quality fuel). The explanation of this assumption is that this "virtual" output associated with the by-products represents the amount of fossil energy which would be required to produce the same amount of feed used in livestock production using oil. According to this reasoning, the production of DDG reduces the relative consumption of fossil energy of society by replacing an equivalent production of feed, and therefore, it should be considered as a net supply of fossil energy to society.

This reasoning is based on a total neglect of the issue of scale. When considering a large biomass production of biofuel, done at a scale which can be associated with the idea of substituting a significant fraction of fossil energy (at least for transportation), the assessment about the "usefulness" of DDG must be radically changed. In fact, Giampietro et al. (1997a) observe: "*Hypothesizing large-scale production of ethanol fuel, for example to supply 10% of the energy consumption of the USA (325 GJ per capita per year), about 3.7 metric tons of distiller's dark grains, the by-product of ethanol production from corn and sorghum (0.83 kg/l ethanol), would be generated per capita per year (TRW 1980, p. 60). This quantity of by-product is more than 37 times the 98.5 kg of commercial livestock feed used per capita per year in the USA (USDA 1992, p. 55). Hence, in large-scale biofuel production by-products should be considered a serious waste disposal problem (and most probably an energy cost) rather than a positive event in terms of energy output*" . . . "*In Brazil a medium plant producing ethanol supplying the energy equivalent consumed by 40,000 people generates a pollution in the effluent water (BOD) equivalent to the sewage of a city of 2 million people*".

3.2 The overall constraint on the quantity of biofuel to be produced

At this point we can finally make a first quantitative reality check on the option of biofuels. An overview of the breakdown of the exosomatic energy metabolism of a typical developed society is given in the upper part of Fig. 11. This is a characterization of the typical pattern of metabolism of a society relying heavily on fossil energy (a mix of coal, oil and natural gas, integrated by nuclear and hydroelectric power). This imaginary developed society has a level of energy consumption of 300 GJ/year (34 MJ/hour) with a split between consumption (30%) and production (70%). The metabolism of the productive sector has an additional split into service and government, building and manufacturing, with a tiny fraction (10%) absorbed by

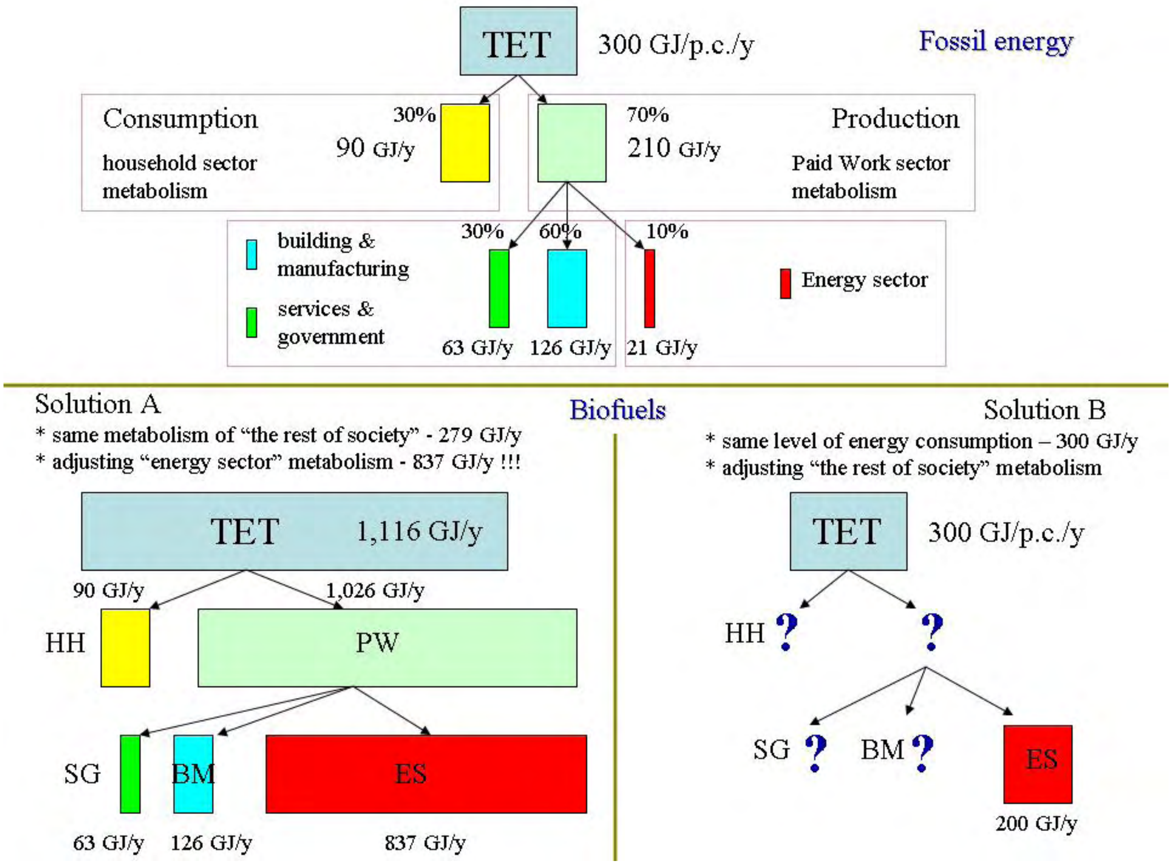


Figure 11. The breakdown of the exosomatic energy metabolism of a typical developed society.

the energy sector. Actually, this breakdown is underestimating the consumption of energy of the energy sector of developed societies. In fact, not all the energy for extraction, refinery and transportation of oil and natural gas is accounted in the energy statistics of the countries which are using imported oil or gas. This represents another advantage of fossil fuels making it possible to externalize the additional energy consumption to extracting and refining oil to other countries. This explains why the pattern of energy metabolism associated with fossil energy is quite different from that that would be associated with a society powered with biofuel.

On the lower part, we describe the same pattern of consumption of the same society powered by a biofuel system with an output/input of 1.33. Because of the internal loop, the energy flow consumed within the energy sector has to be much higher than the energy supplied to the rest of society. We adopt here a value for the overall output/input ratio over the production of biofuel - 1.33 - which is not based on futuristic assumptions of major breakthroughs, but reflecting reasonable estimates (Ulgiati, 2001; Giampietro and Ulgiati, 2005), neglecting the creative accounting of distillate waste as oil equivalent. This value implies the consumption of 3 liters of biofuel in the energy sector per each liter delivered to the rest of society. It is possible to deal with the constraint imposed by this value of technical coefficient by imagining two possible patterns of metabolism:

* *Solution A* (on the bottom left part of the figure) – we keep constant the level of energy metabolized by the sector HH (Household) and SG (Service and Government) at the original level of 279 GJ/year per capita – in the metaphor of the heart, this would represent respecting the pattern of metabolism expected by “the rest of society” - and adjust the energy throughput in the energy sector. With this assumption we would have an internal consumption in the energy sector of 837 GJ/year and an overall consumption per capita of almost 4 times the original (already high) Total Exosomatic Energy Throughput, to reach the level of 1,116 GJ/year per capita (3.5 times the actual level of consumption in the USA!).

**Solution B* (on the bottom right part of the figure) – let us now consider the hypothesis that we keep the original level of 300 GJ/year per capita as the TET of the society and imagine a readjustment of the pattern of energy consumption within the various sectors of the society. Given the output/input energy ratio of 1.33 the energy sector will require an overhead on the TET of 200 GJ/year per capita. The remaining 100 GJ/y per capita have to be reallocated between: PS (considering that additional machinery will be required to make the huge flow of ethanol required to make ethanol); SG (to guarantee social organization and coordination); and HH (related to the material standard of living in final consumption). With a limited supply of disposable energy it is very improbable that a large fraction of the supply of exosomatic energy carriers will be invested in final consumption. In fact, there is a lesson extremely clear from pre-industrial society. In a situation of a shortage of energy supply to be distributed to the rest of society, the building of infrastructures and the development of basic technology tend to take priority over final consumption. The same applies to the need of maintaining an effective administration of the society. We do not want to get into a guessing game of the values which would be taken by the question marks in the lower right part of Fig. 11. What we can say for sure is that a society consuming 300 GJ/year per capita of biofuel energy will look pretty different from a developed society which is consuming 300 GJ/year per capita of fossil energy.

It should be noted that the whole discussion of Fig. 11 does not have the goal of providing a plausible scenario of a society powered by biofuels. In fact, only a fraction of total energy consumption (that in transportation) can be replaced by biofuels. Rather the message of Fig. 11 is useful for flagging the dramatic difference in performance of fossil energy fuel versus biofuels.

We anticipate now, very briefly, a more general discussion on how to characterize the compatibility between the characteristics of an energy sector and the characteristics of the metabolism of a society. In simple terms we can say that economic development entails a dramatic increase in the overall flows of energy (goods and services produced and consumed in a society) at the very same moment in which the amount of working time allocated in the Productive Sector (which includes the compartments in charge for producing food, energy carriers and exosomatic devices) is dramatically reduced. This implies that economic development must be associated with a dramatic boost in the ability of the various activities performed in the Productive Sector to supply the society with the whole flow which is required, while using a very limited amount of hours of labor.

Just to visualize this fact, let’s use a few benchmark values (these benchmark values and their internal relations are discussed more in details in the second paper of this series). A developed society which is consuming 300 GJ/year per capita of exosomatic energy has an Exosomatic Metabolic Rate, Average for Society (EMR_{AS}) of 34 MJ/h. The ratio between:

(i) Total Human Activity of the society in a year (THA), which is equal to the population multiplied by 8,760, the hours in a year; and (ii) the hours of Human Activity invested in the Productive Sector (HA_{PS}), in developed societies is pretty stable (see the breakdown in Fig. 12). Therefore, using standard benchmark values we can assume a value for $THA/HA_{PS} = 27/1$. The amount of working hours in the Energy Sector (HA_{ES}) is a small fraction of the working hours in the PS. We can estimate (again see Fig. 12) that the ratio HA_{ES}/HA_{PS} is smaller than 3%. This implies a ratio $HA_{PS}/HA_{ES} = 37/1$. These two reductions have to be combined to assess the difference between: (i) the pace at which exosomatic energy is consumed per hour of human activity, at the level of the whole society; and (ii) the pace at which exosomatic energy has to be supplied by the energy sector per hour of work.

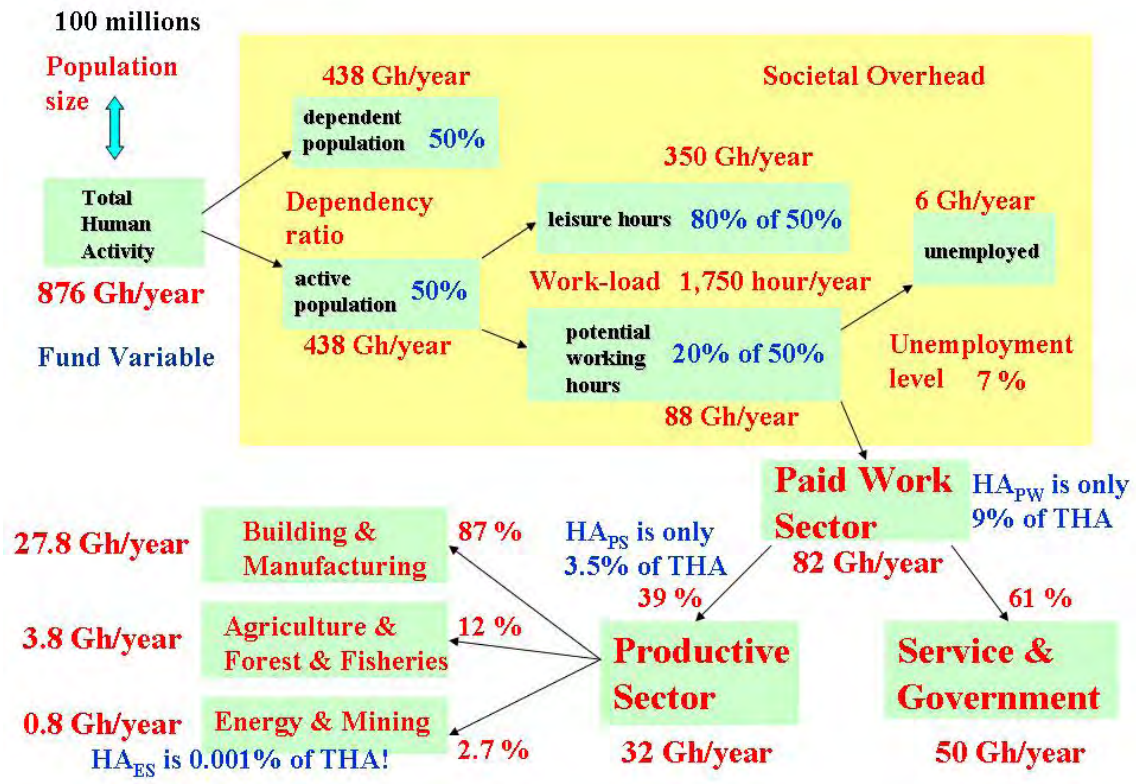


Figure 12. The breakdown of total human activity in developed societies.

In particular we can write the Supply per Hour of Work in ES (SHW_{ES}):

$SHW_{ES} = TET/ HA_{ES}$ (energy sector supply) $= TET \times (THA/HA_{PS}) \times (HA_{PS}/HA_{ES})$

By putting into this relation the benchmark values given in Fig. 12 and a hypothetical level of consumption per capita of 300 GJ/year (34 MJ/hour) we can see that the power level of the supply of exosomatic energy to the rest of society per hour of work in the ES has to be around 34,000 MJ/hour of work (see also Fig. 8b). A value which is three orders of magnitude higher than the average Exosomatic Metabolic Rate (requirement per hour of human activity) for the whole society (EMR_{AS}). Since this point is crucial for the discussion of biofuel this concept will be elaborated more in detail in the next section. In the next section we will also introduce the concept of power density in the supply of energy, when considering the constraints referring to hectares of colonized land in the energy sector, rather than to hours of labor in the energy sector.

3.3 Check on the quality of the supply of biofuel: levels of power supply per hour of work in ES and levels of power density per hectare of land used in ES

3.3.1 Levels of Power Supply of biofuel per hour of work in ES

Let us first consider the difference in the level of power supply per hour of work in ES between biofuels and fossil energy. We can recall here that the example of Fig. 8b indicated the existence of a socio-economic constraint on the minimum threshold of exosomatic supply per hour of labor required in an energy sector powered by biofuel to maintain the characteristics of the *exosomatic metabolism* of Italy in 1999. However that example refers to the existing situation in Italy, which is based essentially on fossil energy, and does not consider the case of a massive production of ethanol in the energy sector. Therefore, the analysis provided in Fig. 8b has to be generalized by using a set of standard benchmark values defining an expected dendogram of splits for the fund variable hours of “Human Activity” over the various compartments making up THA. This is illustrated in Fig. 12. This approach makes it possible to calculate the level of “boosting” that the flow of exosomatic energy supply has to reach per hour of work in the energy sector of developed societies. A standard pattern of expected reductions on the availability of Human Activity within a developed society can be calculated using the following benchmark values:

- 50% dependency ratio (reflecting population structure, education level and retirement age);

- 20% of working time on the available human activity for the active population (workload per year around 1,750 hours, when considering vacations, festivities, and work lost due to morbidity and other causes).

- 7% of structural unemployment.

This set of assumptions entails a societal overhead on the resource Human Activity higher than 10/1. That is, for each hour of human activity invested in the sectors generating added value (that we call Paid Work sector) a developed society is investing 10 hours in activities that implies a net consumption of energy. Moreover, within the Paid Work sector, the vast majority of the activities are not related to the gathering, processing and distribution of energy. As a matter of fact, there is another set of benchmarks that should be used to characterize another series of reductions affecting the final amount of hours of human activity that can be invested in the Energy Sector (lower part of Fig. 12). These reductions are associated with competing requirements of hours of human work for the running of other economic sectors.

> * more than 60% of the total Work Force is employed in Service and Government Sector (SG). In Fig. 12 we used a conservative value of 61%.
>
> * almost 90% of the workers in the Productive Sector (PS) are employed in Building and Manufacturing (i.e. more than 35% of the total work force). Also in this case, we used a conservative value of 87% of the hours of work invested in PS.

* about 12% of the workers in the Productive Sector (PS) are employed in Agriculture, Forestry and Fishery (i.e. 5% of the total work force).

* less than 3% of the workers in the Productive Sector (PS) are employed in the Energy and Mining sector (i.e. less than 1% of the total work force), meaning that a part of these workers are not dealing with the supply of exosomatic energy carriers to society.

Obviously, these benchmarks can change in different countries (for example in the USA the work load is slightly higher and the unemployment lower than in Europe, but on the other hand, the profile of distribution of the work force over competing economic activities more shifted toward services and government and building and manufacturing). As discussed later on, the goal of this quantification is to provide a big picture of systemic features. In fact, when all these reductions are considered we have to acknowledge the fact that only a very tiny fraction of the amount of working hours (HA_{PW}) are actually available for running the energy sector of a developed society: less than 1% of those invested in the PW sector. This fact becomes very relevant when considering that, due to the very high societal overhead on human activity, the supply of working hours in the Paid Work sector is already less than 10% of the Total Human Activity of a developed society.

After adopting this series of benchmarks on the expected characteristics of the exosomatic metabolism, it is possible to calculate the required pace of the exosomatic energy supply at the level of the energy sector. The *Supply per Hour of Work* in the Energy Sector of exosomatic energy to society (SHW_{ES}) must be – at least - 1,000 times higher than the Exosomatic Metabolic Rate of the society as a whole (EMR_{AS}). The factor 1000/1 reflects a given set of expected relations between the different metabolic rates and the different sizes (expressed in hours of human activity) of the whole, the parts and the sub-part. In this example the average metabolic rate of the whole (expressing the requirement at the level ***n***) has to be multiplied: (1) by 2/1 (because of the 50% dependency ratio); (2) by 5/1 (because of the losses due to sleeping, leisure time and unemployment on the work force); (3) by 2.6/1 because of the loss of working time absorbed by Service and Government; and finally (4) by another factor of 40/1 because of the competing requirement of work hours of the other sub-sectors within PS.

This implies that for a developed society consuming in the range of 175 - 350 GJ/year per capita (the higher level being represented by the USA) and using fossil energy as a primary energy source, we can expect the following benchmark values:

* EMR_{SA} (Average Society) of 20-40 MJ/hour.

* SHW_{ES} (within the energy sector) in the order of 20,000-40,000 MJ/hour.

Lets now assume the case in which we want to power a developed society by using biofuels, and lets assume that the biofuel system will be operating with an output/input ratio of 1.33. Again, this value of output/input is based on very optimistic assumptions, but ignoring the creative system of accounting that considers the energy in by-products in oil equivalent in terms of energy supply. At this point, if the consumption of this developed society will be covered by producing biofuel as described by Solution A in Fig. 11, we would have an overall consumption (due to the boost in internal consumption of ethanol for making ethanol, within the energy sector) in the range of 550 - 1,100 GJ/year per capita (when assuming a range of values of the output/input 1.5 – 1.33). This hypothesis would determine the following values:

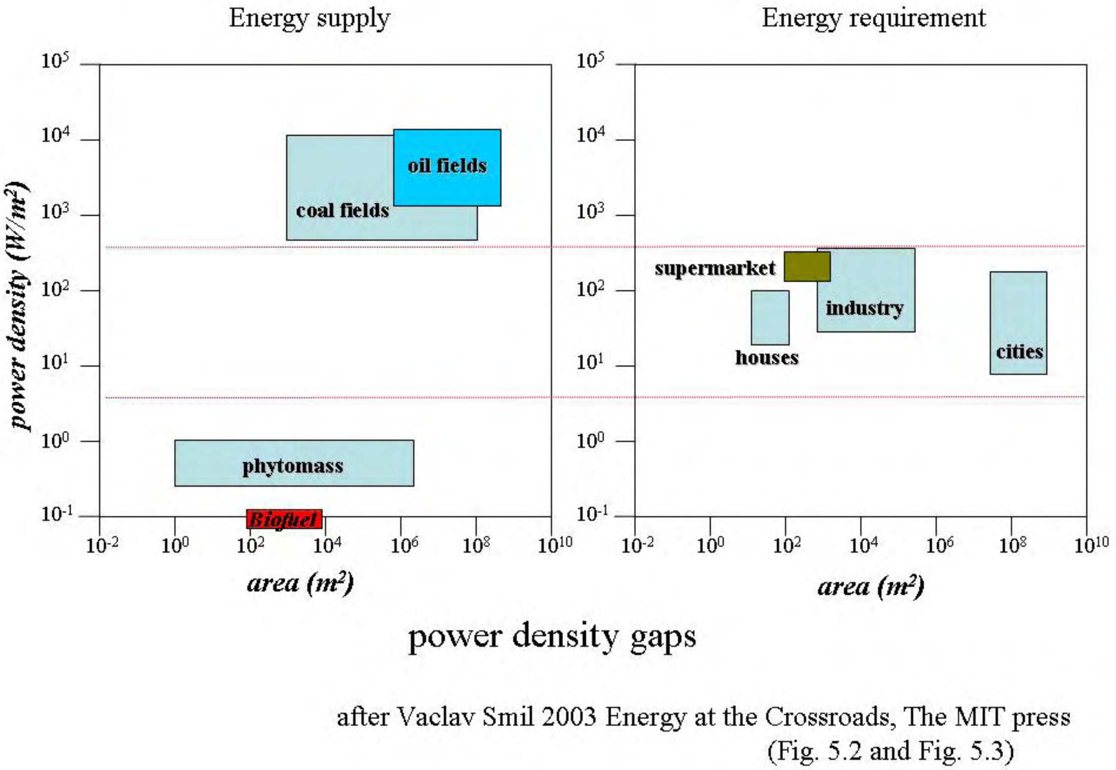
* EMR_{SA} (Average Society) of 62-125 MJ/hour.

* SHW_{ES} (within the energy sector) in the order of 62,000-125,000 MJ/hour.

To have an idea of the power gap between this requirement and the performance of biofuel systems assumed to be totally self-sufficient in energetic terms, we can consider that estimates of the possible Supply per Hour of Work of an energy sector powered by biofuel (when including also the labor required to produce the relative biomass and the conversion of biomass into biofuel over the whole energy requirement associated with the internal loop) are in the order of 4 - 130 MJ/hour (Ulgiati, 2001; Giampietro and Ulgiati, 2005). Therefore, the gap between what is required by the rest of the body and what can be supplied by the "alternative heart/biofuel powered energy system" is in the order of 1,000 – 20,000 times. Obviously, in this type of hypothetical reasoning, individual numbers [e.g. 1,000 times versus 20,000 times] 'per se' are not particularly relevant. Biofuels will never cover the full energy consumption of a society. However, replacing fuels will still represent a significant fraction of it. Moreover, as discussed earlier, there are important non-linearities associated with the accounting of these energy inputs and outputs. When dealing with internal loops and hypercycles the individual figure – the single number output of a calculation - is not the relevant information. That is, with this exercise we do not want to provide any assessment of scenarios. Rather we want to convey to the reader the big picture about a systemic feature of the biofuel energy system. This is what really matters here. In our view, the systemic feature is pretty clear. If the proponents of the biofuel solution are looking for the silver bullet to all our problems - that is, substituting oil in face of its peak, and having at the same time a system which does not generate CO2 accumulation in the atmosphere - then a self-sufficient biofuel system is simply not feasible as a replacement of oil. As soon as the internal loop is considered (as required to have zero CO2 emission), the biofuel process is neither viable nor desirable. Alternatively, if the proponents of biofuel are proposing the production of biofuel based on the use of fossil energy for powering the process (as done right now), then this solution is not desirable. In fact, it does not solve the dependency on oil, it does not solve the problem of accumulation of GHGs in the atmosphere (when considering that 1.2 MJ of oil are used in production and distillation to make 1 MJ of fuel used), it does not solve the problem of high price of oil, and to make things worse it has a remarkable impact on the environment. Assuming that in the future humankind will have plenty of biomass available for energy purposes (a contested assumption indeed), it is much better to use it directly to provide final energy services, rather than wasting all the energy gain associated with the first step of producing biomass in the second step of producing biofuel.

3.3.2 The problem with low power density in the supply of biofuel in relation to land use

So far we illustrated applications of the MSIASEM method only to the fund resource "human activity". However, the same system of accounting can be applied to the other fund resource "colonized land" when looking for the congruence across compartments over the relative metabolic rates per unit of area. That is, it is possible to calculate EMRi and overheads (series of splits) in relation to land uses. When looking at constraints over different rates of metabolism per hectare of different compartments of society we can talk of power density in the supply of biofuel per hectare of land uses. This concept has been suggested by Vaclac Smil (2003) as a heuristic approach to assess the potential of alternative energy sources. The two graphs reported in Fig. 13 clearly illustrate the power density gap between the density of energy consumption of categories of colonized land (land uses) typical of developed societies (on the right) and the density of the production of energy carriers associated with both fossil energy and biomass (on the left). Obviously, in a situation in which the power density in production is much lower than the power density in consumption it will be impossible to have a large fraction of colonized land invested in those categories of land use that are associated with very high density of energy consumption per hectare. As illustrated by the dendogram of the splits of human activity in Fig. 12 various socio-economic activities (in production and consumption) compete for using the limit amount of available human activity. In the same way, there is a competition among different socio-economic activities (in production and consumption) for using a limited amount of available colonized land. To make things worse, human societies also compete, for the stabilization of their metabolism, with natural ecosystems in relation to land uses (colonized land versus natural land covers) – an overview of the two dendograms of splits over nested compartments for both categories of Human Activity and Land Use is given in Fig. 14. That is, within the categories of land use belonging to colonized land, in order to be able to have a certain amount of land invested in consumption with a high metabolic rate per hectare, you must have either: (i) a much larger area invested in land uses in production (with a low power density of the supply per hectare);



after Vaclav Smil 2003 Energy at the Crossroads, The MIT press (Fig. 5.2 and Fig. 5.3)

Figure 13. The power density gap between the density of energy consumption of categories of colonized land (land uses) typical of developed societies and the density of the production of energy carriers associated with both fossil energy and biomass.

or (ii) a small amount of hectares invested in land uses in production (with a high power density of the supply per hectare). For example, it is well known that the number and the size of cities (linked to the fraction of population which is urbanized) found in pre-industrial societies was much smaller than the number and the size of cities found in societies powered by fossil energy. As illustrated in Fig. 13 (based on data of Smil) the density per hectare in consumption of typical land uses in developed countries is much higher than the power density of the supply per hectare of land uses producing phytomass. This graph clearly explains why fossil energy can support a large extension of categories of land use typical of developed countries. In fact, the power density of the energy supply associated with fossil primary energy sources is two orders of magnitude higher then the metabolic rate per unit of area of these land uses. To make things even worse, biofuels, due to their internal loop for production, would imply a further reduction of the already low power density in energy supply of phytomass. In fact, the original power density obtained by the production of the biomass per hectare, would be substantially reduced because of the need of using part of the energy output for the production inputs and for the conversion of this biomass into biofuel.

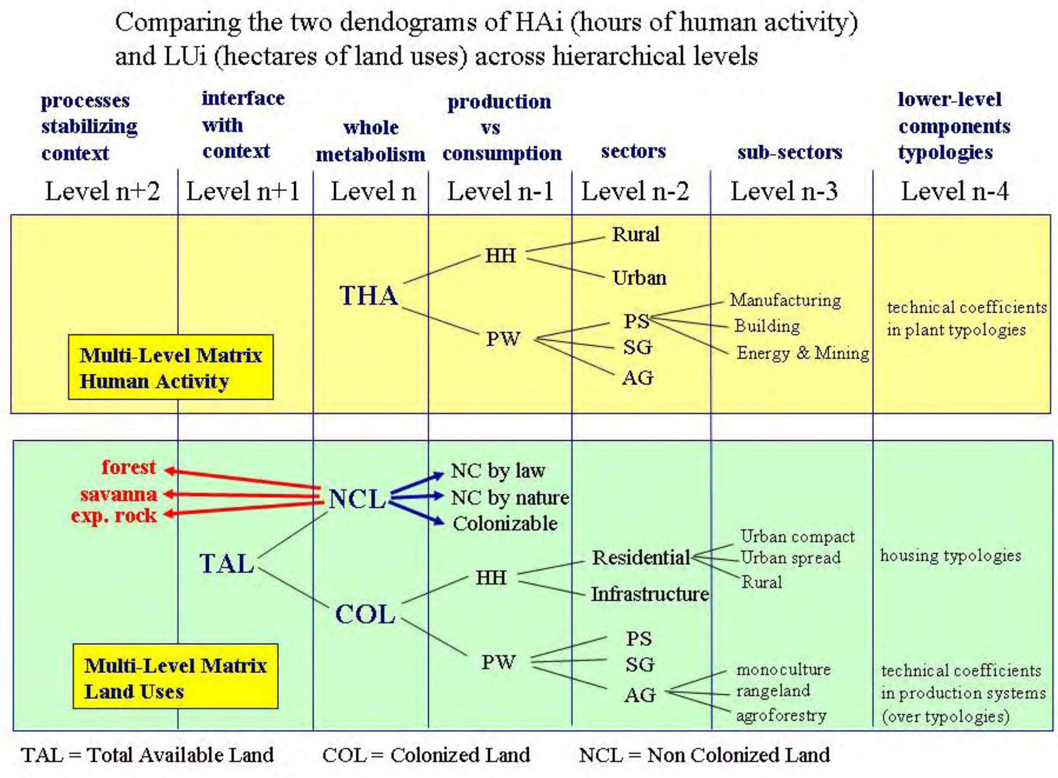


Figure 14. A comparison of two dendograms of human activity and land use.

To better contextualize the discussion on power density of supply and consumption per hectare of land use, Fig. 15 shows - at the world level - the trends of: (i) population size, (ii) arable land per capita, and (iii) energy consumption per capita, over the last 1500 years. It is obvious that the industrial revolution has represented a major discontinuity in these trends. For the first time, in the history of humankind, both population size and consumption per capita could grow in parallel, in spite of a decreasing amount of land per capita available for extracting natural resources. Looking at the graph, it is evident that the key factor of this revolution has been the skyrocketing use of fossil energy. Fossil energy was the magic ingredient that managed to dramatically reduce the requirement of hectares of land per capita in the category of land uses in production for modern societies. In fact, the requirement of land use per capita in agriculture has been dramatically reduced, because food production has been boosted by irrigation and nitrogen fertilizer. The amount of nitrogen synthesized in a year now is equivalent to more than an additional virtual planet Earth. But even more important was the leap in the ability to generate mechanical power. Fossil energy made it possible to obtain power supply based on exosomatic conversion of energy, with almost no land requirement. This made it possible to spread industrial activities away from water-falls, mules and slaves.

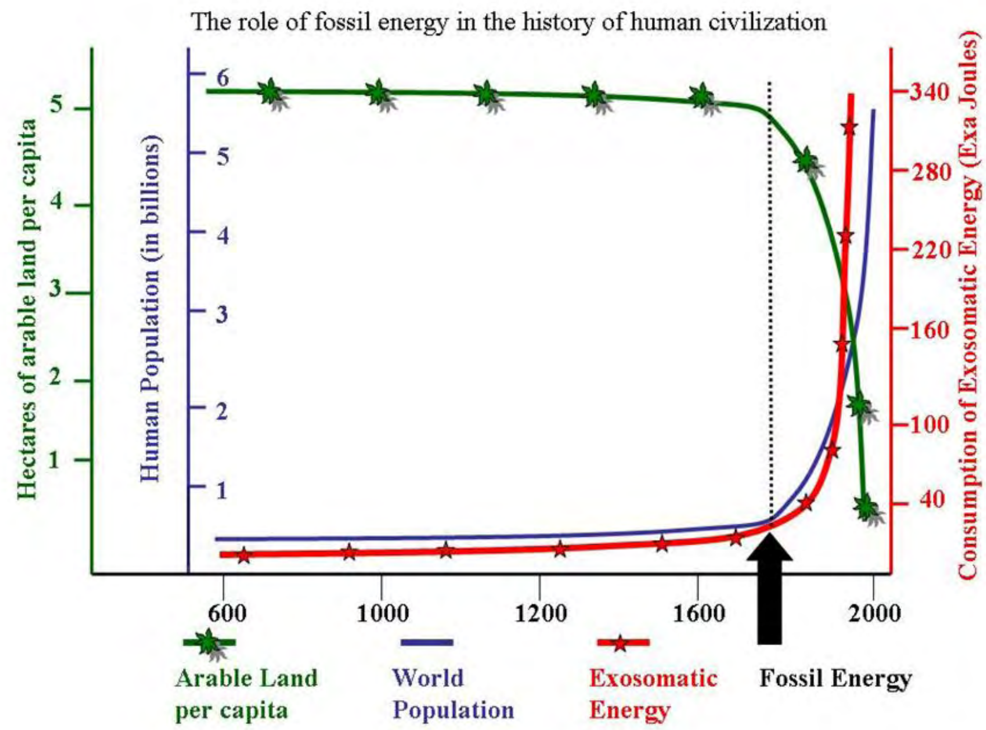


Figure 15. Worldwide trends of population, arable land per capita, and energy consumption per capita over the last 1500 years.

Using the same approach described for the analysis of energy flows against the multilevel matrix of "human activity", we could calculate the amount of land that would be required to cover - using self-sufficient biofuel systems (producing their own energy inputs) – the requirement of exosomatic energy consumption per capita typical of developed countries. Examples of these calculations are given in (Ulgiati, 2001; Giampietro and Ulgiati, 2005). Just to give an example for Italy, the best performing biofuel system would require 30 times more than the entire amount of arable land of that country. However, we do not feel that at this point it is necessary to get into the game of calculating another wave of these hypothetical numbers. We find that the message of Fig. 15 is pretty clear. This illustration suggests, for a developed country, using land to generate power in order to save fossil energy, means suggesting to go against the most powerful evolutionary driver which has been experienced on this planet in the last 150 years.

Land is a crucial part of the equation of sustainability, given that terrestrial ecosystems provide roughly 99% of the world's food supply (FAO, food balance sheet 2002) and that humans are already appropriating (directly or indirectly) nearly 40% of the potential terrestrial net primary productivity at the beginning of the 90s (Vitousek et al. 1986). By the same line of reasoning, but using a slightly different system of accounting, Haberl assessed that prior to the advent of industrial societies - about 200–300 years ago - the human appropriation of Net Primary Productivity (NPP) of terrestrial ecosystems did not exceed 5% of global terrestrial NPP, whereas humanity's energy input currently amounts to about 30% of global terrestrial NPP and is likely to surpass the 50% mark by 2050 (Haberl, 2006). The metabolism of human societies is already using 24% of terrestrial surface for cultivated land. This huge expansion of human metabolism reduced 35% of the original area of mangroves and destroyed or badly degraded 40% of coral reefs (Millennium Ecosystem Assessment, 2003). Obviously, this trend has a negative effect on the preservation of biodiversity and the quality of the environmental services available to human societies.

That is, in spite of the dramatic increase in the need to support the metabolism of global ecosystems, non-colonized land is shrinking at a frightening rate. This is because the widespread and uncontrolled use of fossil energy has made it possible to decouple the increase in the performance of the energy sector (which is able to supply more energy carriers while requiring less human labor) from the relative requirement of land for this task. The fact that today the problem of land shortage is occurring on the sink side (not enough land to sequestrate the excess of carbon in the atmosphere), rather than on the supply side (not enough land to generate the required power supply) should be considered as a remarkable achievement of fossil energy based technology. This is something that never occurred before in human history. This implies that humans have to reduce the actual trends of expanding their colonization of land to the expense of natural habitats for biodiversity preservation (needed to support to the metabolism of natural ecosystems). This worrisome list of disturbing trends clearly indicates that the expanding metabolism of humankind arrived at a size that requires that we re-evaluate the existing constraints to future growth and prosperity. Additional colonization of land either for producing additional food or producing biofuel does not seem to be a move in the right direction.

Conclusion

There is nothing wrong with doing research on biofuels aimed at studying how to better integrate biomass use within the metabolism of developed societies. When dealing with sustainability and alternative energy sources, the more diversified our option space the better. However, the idea of studying how to better integrate the metabolism of human societies with the production of biomass (looking at the multifunctional role that biomass has to play in the sustainability of such a metabolism) is different from the idea of high-input farming for fuel. In relation to the future use of biomass for energy purposes it is crucial to eliminate the dangerous stereotypes currently proposed by the mass media and by those proposing the idea of farming for fuels. Biofuel is not a silver bullet solution to the actual energy crisis. The dream that everything in developed societies can remain the same by just replacing oil with ethanol from crops or plantations is very easy to sell in TV commercials but it is not feasible. It is only generating a dangerous myth in the perception of the general public.

When doing research and integrated analysis of the performance of biofuels one should never focus only on the characteristics of the fuel or only on the characteristics of the process of production of the fuel, but always deal with the big picture. After starting with a life cycle assessment on the production process, one should address the overall compatibility among the process of production, the metabolism of society, and the metabolism of ecosystems embedding societal metabolism. This requires always using a multicriteria analysis, which includes an integrated set of indicators covering different aspects of performance (economic, technical, social, ecological).

In order to better deal with sustainability issues and in particular with the analysis of the interaction of socio-economic systems with the ecosystems embedding them it is important to develop analytical tool kits based on the simultaneous use of different variables (integrated analysis) and to refer to descriptive domains referring to different scales (multiple-scales). In relation to this challenge, we find it useful to adopt the concept of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MSIASEM), a heuristic approach which makes it possible to: (i) check the viability and desirability of possible option at different scales in relation to non-equivalent analyses based on the adoption of technical, economic and social narratives; and (ii) to study the interference that changes in the metabolism of socio-economic systems can imply on the metabolism of natural ecosystems, which are guaranteeing the stability of boundary conditions. An overview of this approach and its application to this issue is given in the second paper of this series.

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