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Review

Is an increased use of biofuels the road to sustainability?*

Consequences of the methodological approach

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Abstract. The global area of planted biofuel crops has been increasing rapidly, but the environmental and social consequences of widespread adoption of biofuel production remain largely unexplored. How do we measure efficiency and net energy of a complex system, such as the interaction between agriculture, human society and technology? This paper provides background and identifies assumptions in its overview of competing and overlapping methods. We emphasize that biofuels, as well as all other resources with their associated processes, should be analyzed as embedded in complex systems. The reason why society looks at biofuels favorably is because the methodological approaches used in the present scientific literature are narrow and far from holistic. What is excluded from the analysis has crucial implications on what is regarded as sustainable.

1 Introduction

The global area of planted biofuel crops has been rapidly increasing, but the environmental and social consequences of the widespread adoption of biofuel production remain largely unexplored [1]. Concerns have been raised about the impact of expanding biofuel crop areas on places such as the Brazilian Cerrado and also the indirect effects on the Amazon forest ecosystems. How would this type of land use change affect the natural resource base and biodiversity? What kind of effects does expansion of biofuel crops have on land tenure and the livelihood of small farmers? What are the effects of intensive use of pesticides and fertilizers? There are concerns for soil loss, high water consumption, soil contamination, pollution and change of the river systems, subterranean and spring waters as well as the overexploitation of rural workers with low wages and poor working conditions [2,3].

Energy technologies, such as biofuels, are commonly evaluated by net-energy methodologies, *e.g.*, Life Cycle Assessment [4]. These are designed to give information regarding efficiency and potential yields, but not sustainability in terms of renewability and the effects on the environment from the use of various energy sources [5]. Non-systemic measures of natural capital rely solely on human perception of value. This shortcoming in methodology ignores the energetic inputs that nature provides for economic systems. Even well-meaning efforts of environmental economists to include environmental values in the economic arena suffer from this shortcoming; see, for example [6]. Severe problems are identified with biophysical measures, such as energy analysis [7,8], since primarily technical energy is considered. Many natural resources and functions that are essential to sustain life on this planet often end up outside the appraisal in today's most widely used evaluation methods.

Mainstream biases are difficult to detect, and therefore rarely questioned. That mankind consistently extracts from nature without regeneration is an assumption of modern society, which rests upon a long history of religious, political and scientific ideas. This fundamental assumption has a crucial impact on sustainability assessments that policy makers rely on for decision making. For example, climate change is seen as one main focus in defining the path towards sustainability, *e.g.* see [9,10]. To combat climate change, biofuels are generally presented as an alternative to fossil fuels, due to lower emissions during the production and combustion stages, favorable energy efficiency and

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(assumed) renewability and ability to help decrease the dependency on oil [11,12]. But how *renewable* are biofuels in reality?

In modern agriculture and forestry there are several non-renewable resources used to produce biomass and to convert it into a form for final use. Those inputs include fossil fuels, minerals, and material embedded in the production of machinery, plastics, pesticides, fertilizers, groundwater, loss of topsoil [1,13–15]. Furthermore, since biomass production requires land use there are also concerns about biofuel production competing with food production, as well as removal of biomass from the ecosystem [16,17]. After harvest there is transport to the biofuel factory, and in the process of upgrading the biomass into a liquid fuel there are many more components that are also non-renewable [14,15,18]. The inputs for producing ethanol in an ethanol plant in Sweden include phosphoric acid, sodium hydroxide, sulphuric acid, enzymes, electricity, liquid petroleum gas, coal, oil, yeast and urea [19]. Could the desirable product rightfully be called a *renewable* fuel?

How is *renewability* defined? To be called renewable, a resource should essentially be inexhaustible —continuously reproduced. Still, by that definition, there are no renewable resources, since the second law of thermodynamics states that i) all real processes are irreversible, and ii) all energy conversions are associated with losses. However, we commonly view a renewable resource as a resource that could be harvested without depletion. Thus, when considering biomass it is a question of scale and time. For example, peat is not considered a renewable resource in most countries, but in Sweden and other Nordic countries, it is defined as “slowly renewable” [20], mainly due to strict rules in the rate of exploitation. Brown and Ulgiati [21] define renewable resources as those used at a speed that is slower than they are renewed, and non-renewable resources are those used faster than they are renewed.

To be *sustainable*, a renewable resource must not only be harvested without depletion. It must also be used without exhausting natural resources or causing ecological damage. As we see it, this is also a definition based on relative scales and time. Synchronizing technology with the right scale-time frame may be the most important factor for achieving sustainability. For example, at the scale of a farm, a well-balanced animal population carefully dimensioned to fit the farm-size and crop sequence enables successful recycling of manure [22–24]. In comparison, a feedlot system with many animals is unbalanced in terms of the degree of production over time, and thus the manure becomes an environmental load [25]. In the case of biofuels, co-products such as feed enhance the overall system performance [26]. But if the concept is extended and the co-products cannot be used they may instead become an environmental load [15]. Large-scale production also interferes with production of ecosystem services. The introduction and management of monoculture crops in the landscape reduces biodiversity and regulatory and production functions compared with a more diverse landscape.

The strong relationship, or dependence, between high yields in modern industrialized agriculture and fossil energy was not discussed until the first energy crisis in the seventies. Odum (ref. [27], pp. 189–190) pointed out that the food we eat was made partly by oil:

> *The high yields from industrial agriculture generated a very cruel illusion because the citizens, and leaders did not understand the energetics involved in the various means by which the energies entering a complex system are fed back as subsidies indirectly into all parts of the network. With conceit, the enriched people imagined that progress in agricultural yields resulted from new know-how in the use of the sun. A whole generation of citizens thought that higher efficiencies in using the energy of the sun had arrived. This was a sad hoax, for people of the developed world no longer eat potatoes made from solar energy. . . . The food reaching the humans is produced mostly by the energy subsidies in support of all the human services required. People are really eating potatoes made partly of oil.*

This statement can be seen as an exception from mainstream scientific view as Odum promotes the idea that a Joule of solar energy does not have the same value as a Joule of fossil energy. The “energy subsidy feed back” in the food system that Odum mentions in the citation above is invisible in net-energy based evaluation methods since every Joule of energy is accounted equal. When we assume that the entire work of nature, from micro to macro scale, and in a geological time-scale is free, then biofuels as a substitute for fossil energy may appear to be a feasible solution. But if the entire geobiosphere is left out of the equation, then how can we really estimate the effects of implementing biofuel strategies? LCA and net energy do not calculate the entire impact on the carrying capacity of the Earth system.

This systems view expands the human perception of value. The way we measure efficiency and how we understand system dynamics relies on both cultural and scientific traditions. What is included and excluded from the chosen analysis may have crucial implications for the conclusions we draw, and our path toward sustainability.

Biofuels are used in this paper as an example of the problems that occur when we base science on an assumption that the work of nature is free. The arguments regarding biofuels are also applicable to all types of social activities, energy resources and technology. The term *Biofuels* will in this paper refer to fuels, gas or liquids, meant to be used for replacing fossil oil as transport fuel, thus excluding less processed biomass such as firewood for cooking or heating.

2 Methodological approaches to energy analysis

All renewable fuels feature technology that is based on fossil fuels —the spinal cord of modern society [28]. Most existing biofuels are of agricultural origin and modern agriculture is dependent on extensive fossil energy inputs [29].

Some studies have shown that biofuel production gives less energy than is needed for refinement of the biomass and that overall, biofuels are far from being renewable; see, *e.g.*, [14,15,18]. In contrast, there are other studies that suggest that biomass is renewable and net positive, see, *e.g.*, [30–32]. An important reason for the controversy is the difference in methodological approaches.

One way to create a better understanding of the issue is to refine basic terminology. Humans utilize energy carriers. There are two kinds of energy carriers, those that have been upgraded to a certain quality by human intervention, and those that have not. The latter are usually referred to as "primary energy carriers", such as oil, gas, coal, biomass, and the potential energy of water and wind blowing. Photons can be regarded as primary energy and the raw material used for producing nuclear power, usually uranium, also carries energy that humans did not intentionally put in the carrier. Those energy carriers, which have been intentionally upgraded, such as electricity, Diesel, ethanol, and hydrogen gas, are usually simply called "energy carriers". This is already confusing, and sometimes both the term *primary energy* and the term *energy carrier* are also called "energy sources". In fact, the only sources of constant inflow of new energy to Earth are photons from the sun, radioactive decay and geothermal heat, and gravitational forces, primarily from the moon and our sun.

It is also important to remember the laws of thermodynamics. The first law states that energy cannot be created or destroyed, only converted, while the second law states that all real processes are irreversible, meaning that losses, an increase in entropy, are associated with them. We cannot create energy, but we can create energy carriers. When electricity is created, 70% of the energy content in the primary energy used is lost as heat (increased entropy) —a typical example of the second law of thermodynamics.

The question is thus how we can ever expect to achieve more energy in an energy carrier such as biofuel, than the primary energy present in the raw biomass itself. As energy carriers cannot be produced without losses, this is of course impossible. Nevertheless, it is easy to calculate a positive "net energy" return as though energy had actually been produced, by avoiding some inputs. It is important to bear in mind that such results, *e.g.* [30–34], thermodynamically, must refer to the conversion of energy carriers into other energy carriers [35]. The input of the primary energy content of biomass is often neglected, while other primary energy sources are accounted for, see *e.g.* [32,36–38]. Again, with the underlying assumption that biomass carries solar energy that is free to use.

Perhaps it can be argued that solar energy is free to us, as we do not need to put in human labor for these processes, and the sun is an inexhaustible source of energy from our point of view, although in a larger, cosmic perspective, it is not. On the other hand, the solar energy received on Earth is a highly diluted form of energy. The entire biosphere is adjusted to this energy inflow and solar energy does a lot of work even unharnessed, such as driving weather systems and ecosystems. These processes generate the essential energetic base for all living creatures on this planet, including human activity. These systems have been attuned to the specific energy density of the solar radiation reaching the Earth's surface over time. Instead of assuming that solar energy is "free" it may actually work as a proxy for land requirement or ecosystem services of different kinds. The theoretical efficiency of conversion of the total incident sunlight radiation by photosynthesis to glucose energy is approximately 13%. In reality, for C4 plants the efficiency of photosynthesis is around 4.5% and for C3 plants around 3% due to a range of physiological losses [39]. This means that significant land areas would be needed to meet a small part of the fuel requirement in the transport sector.

Even though both fossil oil and biomass are primary energy, biomass is much more diluted in terms of energy content. One kg of oil contains approximately 42 MJ of chemical energy. Wood contains less than half that amount if entirely dried, about 19 MJ per kg dry matter. Straw and cereal grains are usually dried down to 14–15% water content, at which they contain around 14–15 MJ/kg. Oil is contained in relatively dense geological formations underground, while biomass harvest requires large surface areas of land —land that is currently used for feeding the global population or for fulfilling other anthropogenic or ecological functions.

Specific methodological approaches for energy analysis omit a variety of different components, as the definition of the energy ratio can be defined in many different ways [40]. Furthermore, the choice of system boundary and the allocation method used has a very large impact on the results [26,41]. It is even the case sometimes that primary energy is aggregated with energy carriers; see *e.g.* [19,38]. It is actually a serious scientific problem that most studies on the viability of biofuels are not comparable with each other [7,42].

Exergy is a concept derived from the second law of thermodynamics in order to facilitate the understanding of one type of energy quality. Energy with high potential for transformation into mechanical work has a higher quality than energy with low potential, so the two should not be evaluated or measured equally. The highest exergy in a work process is the energy that can be transformed into mechanical work in a reversible manner, thus excluding waste heat [43]. The concept enables a more distinctive separation between primary energy with low exergy, such as oil, coal, gas, and uranium, and energy carriers having high exergy, such as electricity, hot water, gas or fuels of different kinds. The exergy concept has also been used as a means of measuring quality of material flows in more complex socio-ecological systems [44–46]. However, Gaudreau *et al.* [47] question exergy in sustainability assessments due to reasons, such as incompatibility between *exergy quality* and *resource quality.* Gaudreau *et al.* [47] also points out that, since exergy only refers to potential mechanical work, the exergy concept cannot describe non-work producing resources.

In statistics the distinction between primary energy and energy carriers is handled through conversion factors. In the BP statistics the criterion for equivalence is thermal heat converted into mechanical work with a factor of 2.6 (the average conversion factor of thermal heat into electricity in the OECD countries), thus it only accounts for thermal heat equivalence [35]. However, the IEA/Eurostat statistics use other conversion factors: 1 J of electricity is equivalent to 3 J of energy commodity if the electricity is generated by nuclear power (relating to the heat in the reactor), 2.6 J of energy commodity if there has been a thermal energy conversion, or 1 J of energy commodity if it is generated by hydro-power, thus truly adding apples and oranges:

Each joule of electricity produced by nuclear plants is accounted as three joules of primary energy commodity. In this protocol it has been assigned a higher weight than the corresponding virtual quantity of fossil energy. On the contrary, each joule of electricity produced by hydroelectric power —the purest quality of mechanical energy— is considered as just one joule of primary energy commodity as if it were a mere joule of coal (ref. [35], p. 56).

Thus, the contributions of various energy qualities in an assessment, such as a biofuel system, are transformed into a common base of heat energy equivalents. This means indirectly that a certain amount of heat energy would have the same value as a certain, smaller amount of electricity, or fuel. However, no matter how much heat we can generate, it would never on its own take the form of electricity. This is because the entire biosphere and a lot of human skill and technology are involved in creating the facilities needed to convert heat into electricity. And even though electricity has the highest exergy, no matter how much electricity we produce, it will never take the form of meat, bread or an apple. Electricity can be used in the process of growing these products, but nevertheless they are of incomparable qualities. Energy and exergy accounting resembles economic accounting in the idea of conversion into a common base without considering differences in quality. Highlighting some of the troubles with this worldview, Hornborg (ref. [48], p. 123) puts it as follows:

Due to the logic of general-purpose money, people thus routinely "trade rainforests for Coca-Cola".

As a response to this discrepancy Giampietro *et al.* [35] suggest that energy and material flows should not be put on a common base. They instead account for these in a multi-dimensional manner, describing inputs and outputs of a system with vectors of several units [35]. This method emphasizes that quality depends on many factors separate from the amount of Joules the energy carrier contains. One Joule of food is not the same as one Joule of fuel. The method of Giampietro *et al.* [35] gives mass and energy balances of several resources, while the energy balance in an LCA primarily manages some inputs of external energy in the process. Emissions from direct and indirect material and energy use are considered in the form of mass balances in LCA. However, a mass balance of any kind does not reflect real impacts on the environment. It is worrying that the most common evaluation method uses this incomplete perspective.

The attempt to shift to "renewable" energies to replace fossil fuels is a shift from a primary energy source to a highly processed energy carrier. *This is a fundamental shift in energy quality.* Before the great pulse of fossil fuels that gave us industrialization, technological development and modern lifestyles, societies relied on renewable and "potentially renewable" resources. Deforestation and depletion of natural resources faster than replacement occurred in previous civilizations before the era of fossil fuels [28]. But society had to be organized differently when we were living within a seasonal time-scale, instead of borrowing energy from the stored credit of millions of years of geobiospheric processes. Referring once again to the above citation of Odum [27] —it is a "sad hoax" that we believe that technological development can change the laws of thermodynamics. It is worrying that politicians, researchers, and those developing technology do not understand this fundamental shift in energy quality. Attempting to convert to "green" technology with tools that rely on highly processed energy carriers dependent upon less concentrated primary energy is like ordering a wolf to eat grass.

3 Thermodynamics for open systems

In order to explain the difficulty in changing from a primary resource to a highly processed energy carrier we will introduce theory describing system dynamics.

Classical thermodynamic theory assumes that the real world is a closed-system model, and since we understand all the different parts of the system we will be able to extrapolate this to reality [49]. The main obstacle to this assumption is that all systems are actually open. And due to energy hierarchy, which means that some processes have larger impact than others, the sum of the whole is more than the different parts. Thus, reducing a system to its different parts cannot describe real, living systems.

If we instead apply the idea that all systems are open and irreducible into their different parts, then we begin to see the interconnectedness and energy hierarchy of the system. Energy transformation processes are interconnected and generate different qualities that have different functions. The output from an energy transformation is always different from the inputs. All inputs and outputs of an interaction or production process contain available energy (exergy), but each input and output is a different kind of energy. Energy transformation is defined as a work process that converts one or more kinds of *available* energy, into a different type of *available* energy. Energy transformations are connected in series and the outputs from one are the inputs to the next. A part of the transformed energy outputs is reinvested in the process where it interacts again in the process, or even controls the process. Typically, in energy transformations within open systems, many Joules of lower quality support processes that generate fewer Joules of higher quality. Odum [50,51] suggested hierarchical self-organization of energy transformation dependency as a fifth law of thermodynamics or open systems. Also, Prigogine and Glansdorff [52] acknowledged that there is a component of self-organization in complex-systems networks.

Energy transformation processes can be arranged in networks and aggregated into series, which can be visualized with energy systems diagrams (see figs. 1 and 2). The energy system diagram depicts the separate scales. Small scales have faster turnover units than large scales of time and space. With each transformation step the available energy decreases, but the quality changes and increases. More available energy of different kinds is required to build up a process that is high in the energy hierarchy. Therefore energy of different types cannot be added to each other without losing the information about the necessary energy transformations required to produce them. To retain this information about different energy quality for different energy forms that are present, Odum introduced two important concepts for capturing this key aspect of open systems dynamics:

i) *Emergy*

Emergy is defined as the available energy of one kind that is used up, direct and indirectly, to generate the inputs for an energy transformation process. Solar energy is most frequently used as the lowest common denominator when processes on the earth are studied. In thermodynamics, the available energy is called exergy, which is the energy in the product excluding waste heat from a process. However, available energy in the Emergy concept includes all types of potential energy, such as water, air, fertilizers and so forth. Even if we are not used to thinking about these as available energy they are indeed forms of potential energy [27].

ii) *Transformity or Unit Emergy Value (UEV)*

Transformity is defined as the Emergy required in transformations divided by the available energy in the transformed product (eq. (1)). For example, the available energy could be the energy contained in electricity (exergy), while the emergy represents all resources, energy and environmental work previously needed to create that product. Thus, a high transformity means that the amount of exergy (available energy) is small compared to what it took to produce the end product. With other words: the higher the transformity the more emergy was required to create a product or process. Transformity is essentially a measure of the energy quality of a certain product or process, showing that it takes energy to transform energy, and all energy transformations are interconnected and interdependent in energy hierarchy:

$$\mathrm{Tr} = \frac{\mathrm{Emergy}}{\mathrm{Exergy}}\,. \tag{1}$$

The energy output of transformations that are tested by natural selection and survived in this process of self-organization (evolution), is reinforcing to the supporting networks by feedback processes. The transformed output must, over time, commensurate with the emergy supporting the process. This means that the transformed product and its feedback to the system must act as an amplifier to the total system performance, or else the system would face degradation of its supportive processes and eventually die out or collapse. This principle of "maximization," or optimization of the system considers both quality and quantity. The concept is suggested to be the forth-thermodynamic law for open systems thermodynamics, presented as "the Maximum Em-Power Principle" [7,51].

When accounting for energy quality some special algebraic notations are used [7,53]:

1) All emergy sources to a process are assigned to the output of the process.
2) By-products from a process have the same total emergy assigned to each kind of output.
3) If a product splits into two pathways, emergy splits based upon the percent of the total energy flow to that pathway.
4) Emergy in feedbacks cannot be counted twice, and by-products, when they reunite, cannot be added to equal a sum greater than the source emergy from which they were derived.

The accounting rules above are necessary for any generative process that includes co-production, interaction and feedbacks. When calculating quality transformations the algebra cannot be conservative, as it is when studying closed systems dynamics. The fundamental characteristics of self-organizing systems, and all living systems, give rise to a non-conservative algebra. Only then, quality *is recognized as being an emerging property (from any physical process) never ever reducible to its phenomenological premises or to our traditional mental categories* (ref. [54], p. 141).

If an open system perspective is applied, it becomes obvious that the work of nature and humans is active in processes such as the production of ethanol. Instead of considering these parameters as free, including them in the analysis makes it clear that the biofuel produced has high inputs of different qualities. To trade a resource with low inputs (oil) to one of high inputs (biofuel) will inevitably have a large impact on how society is organized, and especially on how much production we can have before the load on the supporting environmental systems becomes too large.

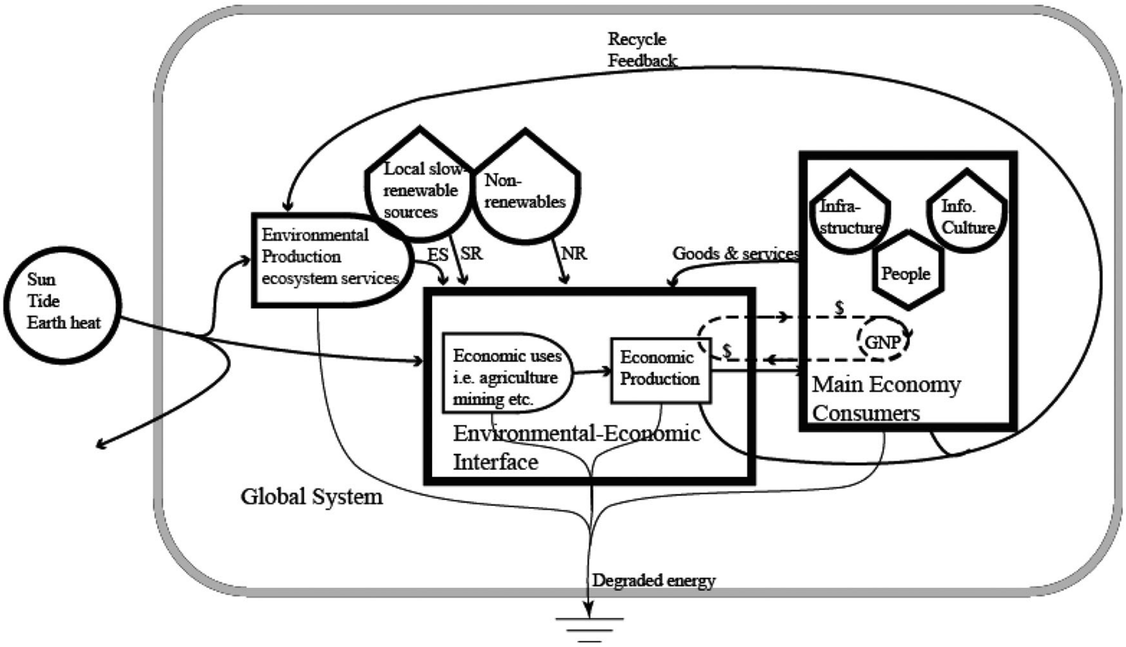

Fig. 1. Dynamics of economic systems within the framework of the biosphere, showing its environmental production, the human economic system, the supporting resource flows, and the feedbacks. Adapted from [7].

Any kind of activity that has a negative impact on qualities such as natural capital and ecosystem services can be included in an emergy analysis if data are available. The emergy concept could help us understand environmental consequences, in contrast to other measures such as mass balances of emissions, which are narrowly focused on one aspect, and do not give information about the qualitative aspects of the systems. It is important to understand that with the emergy accounting approach not only are the sources with forcing functions evaluated, but also are the feedback flows and their impact on the network of necessary generative processes. With those measures, the processes, functions, and resources can be evaluated. This is very different from the energy and exergy concept that represents two physical quantities stubbornly attempting to describe what remains constant. This pure quantitative and conservative system approach is based on the cultural assumption that all resources and processes in the geo-biosphere are outside its records, as they are considered free in the perspective of the market.

4 Dynamics of the interception between natural and human systems

The dynamics of an economic system are represented in fig. 1 by an energy system diagram. The figure shows the different parts of the geo-biosphere needed to produce a biofuel. Starting from the left, we see the main environmental driving forces: sun, gravitational potential and deep heat. These forces support the work done by what we refer to as “Environmental production”. The environmental production processes provide life-support to all organisms in the geo-biosphere while they concentrate resources such as soil, wood, water, minerals and other ecosystem goods and services, thus creating both renewable and non-renewable energy sources.

The renewable energy sources are limited by the flow of the main environmental driving forces to the left in the figure. Hence, the amount of energy that the geo-biosphere receives is more or less constant per unit of time. The environmental production and formation of energy sources usable for humans is the foundation for our economic activities (on the right in fig. 1). Sectors such as mining, industry, agriculture, forestry, health care, education, transportation or any other economic activity cannot be decoupled from the work done by Nature. The environmental production processes are based upon and limited by the inflow of our basic energy sources, such as sunlight, gravitational forces and radioactive decay. Yet, from a classical economic perspective, these resources are provided for free. In the market-oriented neo-classical paradigm that rules our economy of today, it is assumed that natural resources are possible to derive from the capital and labor bringing them to the market [55]. However, Piketty [56] showed that natural resources are a very small part of any countries GNP with this kind of accounting.

The main economic system invests fuels, goods, labor and many other sorts of services in order to access resources generated by the environment. Economic processes are constantly increasing the rate of use of storages of fuels, material and information at various qualities. Storages are not flow-limited in the same sense as renewable energy sources, and increasing the rate of extraction allows growth of economic activity.

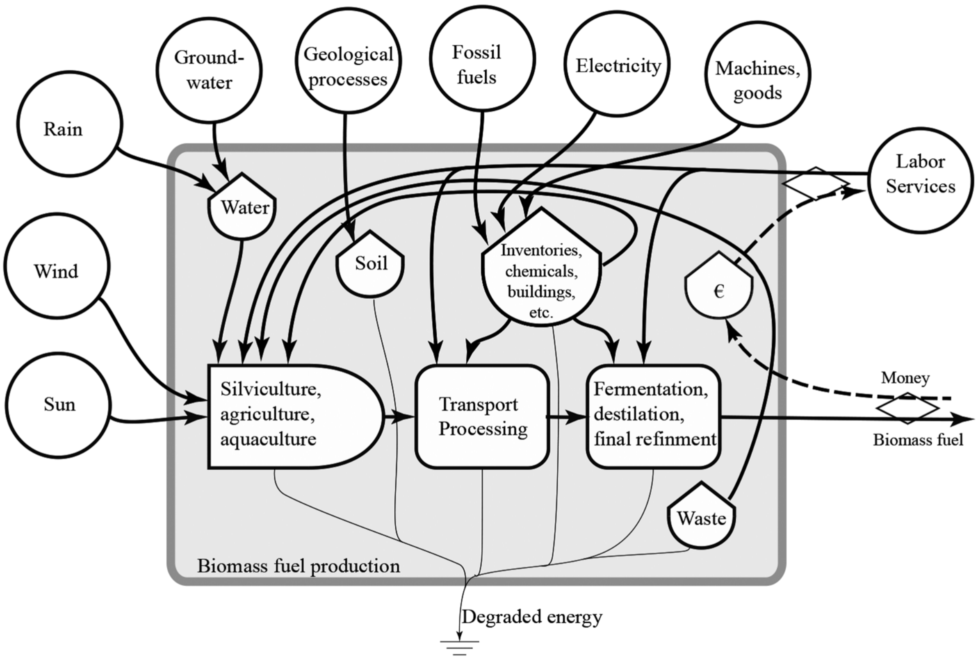

Fig. 2. A generic energy system diagram showing the main steps of converting biomass to fuel. From growing phase, transport and processing to final processing and refinement in order to reach the quality requirements for a transportation fuel.

However, exploitation of the environment cannot proceed at an unlimited rate. Withdrawal at a higher rate than the renewal process leads to depletion of the resource. Some resources, such as forests, soils and groundwater, can be renewed within certain limits. In fig. 1 these are referred to as SR (Slowly Renewable). Other resources, such as fossil fuels, minerals and genetic information, are used up, or depleted, in a very short time period compared to the time required for formation. These are referred to as NR (non-renewable) resources in fig. 1. The depletion of fossil fuels in particular has led to serious disturbances of economic systems [57].

According to Brown and Ulgiati [58], the global biophysical economy relies on 84% non-renewable resources and 16% slowly renewable resources. These alarming results do not support long-term sustainability, and we need a better understanding of this relationship. Sustainability is an issue of the secondary products (SR and NR) generated by the environment, but it is also about interactions among organisms as well as their interactions with the biophysical environment.

All species are active in the dynamics of the geo-biosphere. Each species receives a series of supportive qualities from its surrounding, referred to as ES (Ecosystem Services) in fig. 1. Each species' appearance and the environmental processes associated with diversity generate new qualities that are beneficial for other life forms in the web of life. Degradation of the environment and its ability to generate ecosystem services is a recognized problem. For example, the Millennium Ecosystems Assessment [59] lists the release of toxic substances, climate gases, erosion of soils, losses of forests and other important ecosystems losses due to changed land use activities.

Depending on which part of the system one focuses on, the results of an assessment can vary significantly. From an economic point of view the entire work of the environment is considered to be gratuitous, only considering what was depicted in as the Environmental-Economic interface and Main Economy and Consumers in fig. 1. Energy assessments, *e.g.*, LCA [4], Net Energy Analysis [15], or EROI (Energy return on energy invested) [60] mainly include NR in fig. 1. This point of view leaves out the socio-economic system (Environmental-Economic interface and Main Economy and Consumers fig. 1), the true energy sources (depicted on the left in fig. 1, Sun, Tide and Earth Heat), as well as the environmental production of ES and SR. A socio-economic study, *e.g.* [61], may include NR, but leaves out ES, SR and the energy sources to the left in fig. 1.

An energy system diagram showing the main steps of converting biomass to fuel is shown in fig. 2. The system border is open for fuel to flow in either direction and does not represent a closed system of traditional thermodynamics. It is rather as if one was looking through a window. One sees whatever one gives attention to, but the surroundings are present in one's perception as well. Therefore we call this dynamic border "The window of attention". To operate the activities within the window of attention there are a range of driving forces required from outside the window. These forces include different forms of energy, such as sun, wind, rain, groundwater, fossil fuels and electricity. Some of them are more aggregated than others. For instance, Geological processes are an aggregate, and Machines and Goods include all different tools, machines, chemicals and other goods. Labor and Services include all types of labor required directly and indirectly to operate the processes within the window. In the example of biomass, Labor and

Services include the labor needed to extract and upgrade all resources brought in for biomass fuel production. Notice that money flows occur only between people. Money is paid directly to labor, and indirectly to labor needed for extraction and manufacture of various resources. No money is paid to the work of the geo-biosphere for concentrating and transforming material into extractable resources.

The growing phase is included in the window of attention —silviculture, agriculture and aquaculture. These processes are to some degree driven by flow-limited, diluted (low transformity), renewable energies in the form of sun, wind, and rain. However, they also involve more processed and concentrated non-renewable energies, such as machinery, fertilizers, and other goods, labor and services necessary to manage the growing phase. The process of transforming the harvested biomass into fuel useful for our transportation technology is almost entirely driven by non-renewable energies [15, 62, 63].

The many types of energy identified in fig. 2 are necessary for the fuel to be generated. Both figs. 1 and 2 exemplify how products from the environmental production interact and embed within processed products that are handled by the economy. In short, nature's work is commercialized, and the economic interchange is used to run the technological processes. But the actual money is paid to people, and nothing is paid back to the environmental processes.

5 Efficiency of open systems

Efficiency can be measured in different ways that depend on our choice of systems view. Previous attempts to explore energy use in human-dominated ecosystems gave rise to very different approaches, some based on direct and indirect fossil energy use, energy related economic aspects, or environmental concerns. Different energy evaluation methods provide different perspectives and sometimes hardly comparable results.

Efficiency in the business world refers to working or producing effectively, with no unnecessary waste of time or resources [64]. Efficiency in this case is often measured by the amount of money or hours or amount of production per invested money or time unit, or area when evaluating agricultural yields in kg of main harvested crop per ha, for example. With this kind of efficiency measure by-products, such as straw, are not included as a yield. So a cereal with a long straw, for example, grown as forage for animals, will be evaluated as having lower "efficiency" or yield, even though it is perfectly suited for the purpose of producing both straw and feed, and the total biomass production on the field may be the same as when growing a cereal with shorter straw and larger proportion of the starch-rich seed. This systems view also generates problems with handling multi-functionality, and thus risks discrediting farming management techniques that use intercropping for better uses of ecosystem services. The trend in farm size at present is towards larger farms [65], and there is some controversy regarding the productivity of smaller farms. However, studies of smaller farms with multi-functional land use, much like a larger scale of gardening, have in several cases shown larger total productivity than the productivity of larger, less diversified farms [66–71]. This is known as the "paradox of scale" or "inverse farm size - productivity relationship".

The "efficiency" of different farm systems can also depend on what parameter is measured. Large-scale farms tend to have higher labor productivity, while smaller farms may have more efficient land use [72]. The Green Revolution may have contributed to increased yields, but at the cost of dramatically reduced resource use efficiency in agricultural production [29].

Energy balance, mass balance or LCA fall into the "economic efficiency" way of thinking. In thermodynamics, however, efficiency is mainly a concept derived from heat-processes, where the Carnot cycle represents a thermodynamically ideal engine with the maximum efficiency given a certain temperature difference. Here efficiency, η, is a dimensionless ratio or percentage [43]. For example, when coal is turned into electricity at a power plant the efficiency is about 0.3, or 30%. This means that 30% of the chemical energy contained in the coal is transformed into electricity (which equals the exergy), while the rest is turned into heat. Here one recognizes the two first laws of thermodynamics: TI) energy is conserved —one cannot create nor destroy energy—, and TII) all energy conversions result in heat losses —an increase if entropy. When one speaks of *net energy balances*, or *energy return on investment*, the very terminology deviates from the fundamental laws of thermodynamics since energy cannot be produced. No real process will end up with more energy than what was inserted. However, measuring how much of the desired work (or product) is obtained from each unit of energy invested into that task (or product) has become one of the most common definitions for efficiency in resource physics.

According to Carnot himself it is not quite a question of efficiency, but of optimization:

We should not expect ever to utilize in practice all the motive power of combustibles. The attempts made to attain this result would be far more harmful than useful if they caused other important considerations to be neglected (translation from Carnot, 1824 [73]).

He stresses that safety, strength and durability are more important. Carnot writes this referring to an engine —an altogether human-made technology where we have absolute knowledge of all the parts in the process. However, nature and our interaction with it is a system where we still have very limited knowledge in comparison. Since nature, with all its earth processes, living creatures, and human societies are operating together as one self-organizing system; it looks more like a living organism than as a combustion engine [27,74]. Thus the predictability of altering a few parameters is very limited.

Evolution can be seen as a process of increasing efficiency in the way systems and processes become more and more fit over time. Perhaps it is more appropriate to view this as an optimization process instead, following the Maximum Em-power Principle mentioned in sect. 3. Maximum efficiency and maximum power develop in subsystems at times, but the system as a whole will only be resilient if the system is empowered at all levels. Letting money or yield define efficiency leaves out the supporting processes and resources, which is not surprising as these measures are socially constructed and only account for human exchanges. When our interaction with nature degrades supportive processes, indirect economic measures such as monetary values on ecosystem services are introduced as a way of accounting for the drains. This way of accounting, however, rests upon the dualism of man and nature, suggesting that we are not part of those systems that we are in reality interacting with [75]. Instead of being a cost if lost, an ecosystem service should be viewed as a gift essential to the desired activity.

The classification of resources as waste can also be seen as a result of a cultural norm and assumptions within the scientific society. Resources that do find a market but have no economic value are often classified as waste. In an open systems perspective where self-organizing systems are operating, the word waste has no meaning. Since all types of energy, material, and information are part of the metabolism of the geo-biosphere, they are essential, but of different quality and at different levels in the energy hierarchy.

6 "Living-system" perspective versus "mechanistic-system" perspective on biofuel systems

A living system is characterized as open, interactive, self-organizing, evolutionary and process-oriented. Systems that have a long-term proven sustainability through the history of evolution are those that survive [76]. Classical thermodynamics was developed through studies on idealized closed systems. Yet, as all living systems are open, the characteristics of closed systems may be inappropriate for describing how living or open systems function.

The mechanistic/reductionist-system perspective is based on studies of idealized closed systems. The entire society is seen as an engine, and biofuels are merely a means of changing fuel while keeping the engine intact. This is of course a simplification, since, even at small scale, the combustion engine must be adjusted to the new fuel. But in the mechanistic world-view it does not matter what kind of work has been invested in producing the fuel. Since energy is conserved a Joule of one kind is equal to a Joule of another kind. The solar energy is free, rain, wind, time and space are free as well, and we do not need to account for or even acknowledge the energy quality for any reasons except technical reasons, such as which materials to use. Since most supporting processes are not identified in this world-view, and the methods of analysis are partial, the substitute fuel is considered renewable. Efficiency is optimized for one parameter, such as yield/ha, \$/h, or J biofuel/J fossil fuel.

From the living-system perspective we recognize, with "common sense" but also from a quantitative perspective using emergy analysis, the many joules of lower quality invested into the biofuel process yield a higher quality but lesser quantity. As the transformity of biofuels can be high [8,15,27] biofuels require a large support from the environment, often using a portion of non-renewables, so biofuels cannot easily be treated as a substitute for fossil fuels.

Emergy analysis of biofuels may help us to understand that evolution has already attempted this trial and evolved different species that convert biomass in their digestive system into both mechanical work and other extra "gifts" of ecosystem services, which reinforce the system as a whole. The ecosystem is efficiently constructed throughout billions of years of evolutionary trial that the different species hardly compete with each other. Instead the species co-exist, providing each other ecological habitats as a feedback. Asking stronger animals that feed on grass for help for transportation and food production from a "living-systems" perspective turns out to be a successful symbiosis that generates several reinforcing feedback processes [77]. In this systems-view paradigm, efficiency is defined as processes that enhance the entire system (maximum empower). For example, a living creature transforms biomass into work, meat, fur, milk, manure, hosts for insects and microorganisms, organizes the environment for grasses and flowers and pollinators as they graze, and so on, giving back to the system at many different layers simultaneously. In contrast, the produced biofuel used in combustion engines only generate mechanical work.

Algae for biofuel production have recently received some attention [78–80]. We denounce this idea for the same reasons already elaborated. In these algae factory farms, the algae are removed from their natural environment. All photosynthetic producers require minerals and essential structures for survival. But in closed systems with pure populations, these elements are provided through non-renewable societal structures and fossil resources. This is similar to the case of biofuels from agriculture. Overall, our society relies on stored photosynthetic energy from millions of year in fossil fuels. The quantities are enormous and are coupled to almost two centuries of continuous growth and expansion of these resources. It is not realistic to assume that any renewable process can compete with the quantity and quality of fossil fuels that support our current system.

Our society functions more like a living organism than like an engine [81]. It is clear that if we want to change our energy base to low concentrated primary sources, such as sun, wind and biomass, our modern society will need to be very different in many ways. It does not matter exactly what kind of technology is studied, whether it is algae production farms, ethanol, biogas, ligno-cellulose based fuel, solar cells or wind power technology. These technologies signal "sustainability" only if the analysis is partially interrupted, by leaving out the supporting systems.

It is apparent from an open systems perspective that the processes and flows of the many different forms of energy shown in figs. 1 and 2 are necessary to the biosphere. No processes and no flows on the right in the figures can exist without those processes and flows on the left, and vice versa, due to the feedbacks flows from processes on the right back to the processes on the left. This interconnectedness is necessary for any studied process. When processes are evaluated in terms of heat value or exergy value a substantial portion of the flows, especially those from the top of the energy hierarchy, is undervalued or considered insignificant. Consider the example of labor in energy analysis; see [82]. The energy flowing directly and indirectly from environmental processes to an economic activity is excluded from the analysis because it is considered free of charge. Those flows are associated with large quantities of heat or exergy. In the emergy analysis evaluation methods it is instead assumed that they all are of importance and essential for the entire system. The flows from each process can be expressed as the amount of energy of one form it took to produce the final form of energy.

7 Summarizing discussion

A major reason for the political promotion of biofuel is the climate change discussion, and the conclusion from the 2007 International Panel of Climate Change (IPCC) [83]. But why, or how did these authorities come to the conclusion that these are renewable fuels? The mechanistic world-view rests upon a long tradition of beliefs or assumptions that undermine the direct relationship between man and nature. The scientific tradition is based upon reductionism that separates reality into its different parts with an underlying assumption that the world can be understood only if we have knowledge about each part [49]. Since the volume of data would be too large if all parameters were included, science has constructed models from idealized closed systems to predict real process behaviors. But a fundamental characteristic of all real, living systems is that they are open. Why do we believe so strongly that the idealized closed system is a good approximation for reality?

As we see it, the reason biofuels are considered renewable is that fossil fuels are of such high quality that they have allowed us to ideologically free our economy from nature, so that resources and supporting processes valuable to the biofuels are not included in the method of analysis. The renewability of biofuels is a product of a partial flow-system analysis. There is no quantification of the renewable flows in the method used in the net-energy based methods referred to above, and still the product is presented as renewable. Another essential element that should be quantified as a component in biofuel production is the social liabilities to which poor countries are subjected to when massive small farmers migrations result from large-scale ethanol. We cannot use this science as a base to navigate towards sustainability. All processes are driven by renewable ecosystems, so why are those ecosystems not included in the analysis? We interpret this to mean that those ecosystems are free, extra, and outside the system, which is a mainstream idea buttressed by classical and neo-classical economic theory. But this theory has consequences regarding sustainability, since the biofuel process requires several other flows than those of fuels and biomass, such as material flows and environmental work. For example, no matter how many liters of ethanol we can produce, ethanol cannot build a tractor on its own. The entire recipe is needed, yet we limit the analysis on which we base our decisions, painting an unrealistically rosy picture of biofuel as an energy substitute.

Transformations that are enriching contribute to vital systems, but transformations that detract will in time degrade the entire system. Artificial amplifications can be created, but they consume resources and eventually degrade the system. The impact of fossil fuel use on the entire Earth system is a good example. The ratio of the emergy yield of oil to invested emergy is still high [7,84]. This suggests that oil production is inexpensive as a resource to exploit, which is a reason why we were able to increase its production and use exponentially over almost a century to generate a complex society based on current production of 30 billion barrels per year [85]. The yield ratio of ethanol is very low (see *e.g.* [7,81]), which suggests that it takes many resources to produce it. Thus, a large-scale expansion would probably not even be possible or desirable. Fossil fuel has had space and time to its advantage in its development, but it is used very fast in relation to its renewal time. Biomass is non-renewable based on its inappropriate scale and speed of use.

The basis of our critique regarding mechanistic world views, such as LCA and energy analysis is from an open systems point of view. We do not reiterate previous critiques of the open systems point of view from the mechanistic point of view, however, there are those who have done that [86–88]. Rebuttals to the critiques have also been published and the validity of their proof has been questioned [89,90]. Verwijst [91] stresses that there is a side of Emergy analysis methodology where *there is a great deal of confusion and also some doubts regarding the relationship of emergy to traditional and established thermodynamic concepts*. This is true in that the idea of emergy relies on an open systems view, while traditional thermodynamics relies on a closed systems point of view. From this perspective, the emergy concept may be a development of traditional thermodynamics as it is also included [27], and not necessarily opposing it. Giannantoni [92] further defines the mathematics for emergy and its relationship to established thermodynamics.

“Renewable” has nothing to do with “net energy balance” of support energy. For example, exchanging 2 liters of fossil oil for 10 liters of ethanol is still by definition not renewable. It is just using less oil than the system it is compared with. And who is to say that the current system it is compared with is a desirable system? The environmental problems are piling up alarmingly, along with social issues of malnutrition, famine, poverty, and inequality, to name a few [93]. Why do we still want to keep the current system? True sustainability may be reached when we understand that what we give back to the system matters. Everything is an ecosystem service, and humans are just as connected as everything else in the web of life. Amplifying feedback is necessary for sustainability. How is that achieved? The fact that we have simplified and rationalized the current landscape may be one of the elephants in the room.

Odum [7,51] points out that energy qualities are being mixed together; that a Joule is not equal to a Joule. This creates the logic that higher intensity equals higher output, which is a rational outcome only if we assess energy without including quality. If we included both the direct and indirect underlying work of nature, the answer to the question of biofuel viability would be different as it becomes obvious that there is no real energy return. This is actually a more accurate reflection of the first law of thermodynamics. When the real processes behind the product are excluded from analysis, along with a short space and time perspective, we have to overrule the first and second laws of thermodynamics.

A quantitative system perspective rests on classical mechanics, and if an open systems view is applied with this perspective the amount of data required would outrun our abilities. So methods are devised that limit the amount of information. In LCA and its relatives, (ecological footprint, energy analysis, EROI) the data are restricted by the introduction of system boundaries. Emergy synthesis, in contrast, maintains open system borders, and it is possible to zoom in and out in different scales. The strength of this approach is that it keeps the interdependencies to the environment, but one of the challenges is that one needs an open systems understanding to interpret the calculations. Thus two separate worlds are appearing.

We also see shortcomings in the choice of system perspective regarding the environmental impact when emissions are quantified. One measure is the emissions at the “chimney”, but not what happens in the environment. What was required to make a certain product? There are unique processes in many cases leading to loss of biodiversity and ecosystem functions. This is crucial information for decision makers in order to navigate towards sustainability and a living planet. Sustainability is frequently divided into ecological, social and economic sustainability. However, we emphasize that it is the same system, and that ecological, social and economic sustainability are inseparable. Social and economic sustainability cannot be divorced from their fundamental environment (nature —the bio-geosphere). Social health cannot exist without ecological health.

In 1977 Ilya Prigogine received the Nobel price with his research on complex systems and self-organization. Odum received the Crafoord price in 1987 with a rigorous theoretical concept and methodology to handle self-organizing systems. Despite this recognition, there is little awareness regarding principles of living systems when it comes to sustainability. Prigogine writes in the book *The end of certainty* (ref. [94], p. 7):

> *… we believe that we are actually in the beginning of a new scientific era. We are observing a birth of a science that is no longer limited to idealized and simplified situations, but reflects the complexity of the real world, a science that views us and our creativity as a part of a fundamental trend present at all levels of nature.*

Regardless of these optimistic words, written 20 years ago, research on sustainability, energy, technology and systems analysis are still dominated by reductionist methods without an open systems view.

8 Concluding remarks

The arguments in this paper can be used for any kind of system, and we use biofuels as example of the difference between an open (living) systems view and a closed systems view.

Biofuels, to a large extent, depend upon non-renewable resources. As oil loses the net return on invested energy, biofuels become competitive first when their ratios are of the same magnitude. But the amount of fossil fuels that we want to replace is not achievable. Attempting to structure a society based on biofuel would draw resources from societal organization, due to the limitations of non-renewable resources, the overexploitation of resilience (biodiversity) and the relative turnover time of renewable resources.

Biofuel literature avoids descriptions of renewable resources in those products that are considered “renewable”. The literature avoids the issues of the first and second law of thermodynamics —that it takes energy to convert energy into new forms. Research limits the analysis on various inputs to the biofuel process, which are crucial for sustainability. In a monetary sense they may be free, but when crucial ecosystem functions are lost we see that our activities depend on them. Since assessments are only partially explored on subsystems, we do not know if it is a real optimization on resource claims, since the supportive systems are not included in the analysis. Thus most analyses are misconceiving, while other open systems studies suggest that the claims on the geo-biosphere are much larger than evaluated.

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