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Hidden costs of a typical embodied energy analysis: Brazilian sugarcane ethanol as a case study

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ABSTRACT

Worldwide human production systems are tightly coupled to fossil-based energy, the source of which will not be available at low cost in the foreseeable future. Alternative energy sources are being sought for, among which those derived from biomass are considered to have great potential. Brazilian ethanol sugarcane produced at a large scale is being classified in scientific papers and politics as a renewable energy source. However, only the energy return on investment (EROI) and/or the amount of CO_2 released to atmosphere have been considered as indicators of renewability. This work aims to discuss some theoretical points, within an embodied energy analysis, that make its use inappropriate for answering all issues related to the concept of renewability. Emergy accounting (with an "m") is used as a comparative tool and the Brazilian sugarcane ethanol is evaluated as case study. An EROI of 6.7 for ethanol was obtained, showing that for each unit of "commercial energy" invested within the process, 6.7 units of another kind of energy is obtained – this index shows an excellent value for energy efficiency, but it does not reflect the renewability of ethanol. On the other hand, emergy accounting shows a renewability index of 19%, indicating a low rating for sugarcane ethanol. All scientific methodologies available to assess potential energy sources have their pros and cons, but the analyst must be aware that each methodology supplies different indicators with different meanings. Energy analysts should use methodologies appropriately, avoiding wider conclusions not actually represented by indices calculated.

1. Introduction

Petroleum, natural gas, and coal are currently responsible for providing almost 87% of the total primary energy consumed worldwide, reducing natural reserves at a rate that will probably cause them to become unavailable at low cost in the next decade [1–3]. Additionally, it is recognized that fast consumption of fossil energy is the major cause of the current climate change [4]. In 2005, the major economies of the world, including the G8 and 5 developing nations (Mexico, India, Brazil, China, and South Africa), along with the United

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Nations, the International Energy Agency, and the European Union, launched the Global Bioenergy Partnership and met to discuss ways to promote the sustained use and production of biofuels around the globe, reflecting growing concerns for finding viable substitutes for petroleum. Climate change and peak oil have renewed the interest in alternative energy sources, and for this reason biophysical assessments rather than economic ones are getting back into scientific discussion. According to Giampietro [5], after the failure of energy analysis in the 1970s to become politically relevant in decision making, biophysical analyses are currently being compared to economic analyses. The need for energy analysts to avoid the mistakes made in the past with regard to renewability and sustainability measures is more important than ever before.

In Brazil, large-scale sugarcane ethanol production is being considered as an excellent alternative for fossil fuels [6,7] and it is being labeled as a sustainable or renewable energy source [8,9]. Sustainability in this work refers to "strong sustainability" concept, in which human capital and natural capital are complementary, but not interchangeable. A resource can be considered as renewable if it is replaced by natural processes and if replenished within a shorter term than its use term. In this sense, knowing that any production system often demands both renewable and non-renewable resources, the existence of a renewability degree for the output product can be noticed. Specifically for human-dominated systems production, the renewability degree is rarely close to 100% as advocated as for ethanol fuel production – this is due to the fossil fuel-based development pattern adopted by the majority of the economies during the last century. Notwithstanding, the Brazilian government intends to continue increasing large-scale ethanol production, projecting the following scenario: from 2010 to 2019, ethanol demand is projected to increase 90%, reaching 64 Mm^3 per year; 103 other large-scale ethanol plants will be installed to meet that goal; the current 82,000 km^2 of sugarcane will increase to 119,000 km^2, taking into account a scenario of improvement in sugarcane and ethanol productivity [10]. Even recognizing that ethanol fuel features a higher renewability degree as compared to fossil-based fuel, many doubts are being raised about the environmental, social, and energetic performance of its large-scale production [11–14].

Some works [6–9,15] indicate that ethanol is a sustainable or a renewable energy source, but their arguments are often based on two aspects only: the Energy Return on Investment (EROI) index and the Carbon Dioxide (CO_2) emission. Both indices offer useful insights on the energy efficiency and environmental load on a local scale for the analyzed system, and their scientific importance is recognized due to climate change and energy scarcity scenario. However, the following doubt is presented: Can EROI and/or CO_2 emission reveal the renewability of alternative energy sources including large-scale ethanol production? According to Hall et al. [16], a consensus about the implications of the EROI of various fuels is needed. Many of the EROI arguments are too simplistic or incomplete to describe the renewability and sustainability of various energy sources. In traditional embodied energy analysis, only a part of the whole system is accounted for, thus disregarding important energy and matter flows. The window under interest is reduced and great deal of important information is lost. As a result, such omission could influence the scope of inference for results from these analyses. In this sense, the present work hypothesis is that large-scale sugarcane ethanol production, as it is currently carried on, cannot be labeled as a renewable energy source if based solely on an EROI index. Renewability could be addressed only after one's understanding and quantifying the system flows of energy and matter through a systemic viewpoint, this is where emergy accounting (emergy with "m") may be a useful alternative approach.

Similarly to Embodied Energy Analysis, Emergy accounting has been criticized (e.g., Sciubba and Ulgiati [17]; Hau and Baski [18]). Nevertheless, the systemic approach in the emergy methodology and its capacity to account for different forms of resources used previously to make a product (from nature and human economy) make it a more powerful tool than Embodied Energy Analysis to show systems renewability [18]. In this sense, the aim of this work is to make a critical assessment of the use of EROI as an indicator of renewability, and for this purpose, a large-scale sugarcane ethanol production system in Brazil is considered as case study.

2. Embodied energy analysis

One potentially useful alternative to conventional economic analysis is Energy Analysis (EA), defined as the process of determining the energy (free energy in thermodynamics terms) required directly and indirectly to allow a system to produce a specified good or service [19]. Energy here is defined as the physical ability to do useful work, where useful work is done when a body is moved by a force. The physical ability to do work is represented by the enthalpy of the fuel, so the numerator and denominator of an energy efficiency index are typically measured in heat units such as Joules. The accounting framework for EA has been in the literature for 30 years, being subject to inherent, inevitable difficulties which must be dealt with explicitly – examples are questions of system boundary, how to merge several kinds of energy, energy credit for byproduct. Further information about initial assumptions within an energy analysis and their interference on the results can be seen at Cherubini et al. [20] and Malça and Freire [21]. Those issues are fundamental and research has shown that they can be overcome only by judgmental decision [22].

Embodied energy analysis, considered as an item under the general label of energy analysis, is being applied according to the International Federation of Institutes for Advanced Study (IFIAS) conventions, accounting for the amount of "commercial energy" (fossil fuel as numeraire) that is required directly and indirectly by the system or process to make a determined good or service. It accounts, basically, for fuels, electricity, fertilizers, and other chemicals in terms of fossil oil equivalents demanded to produce them. The most important result of the embodied energy analysis is the total oil equivalents that go into the system boundaries (Input) in relation to the product expressed in its energy value (Output). This output/input ratio is called as Energy Return on Investment (EROI) (see Fig. 1). The results can also be shown by dividing the total

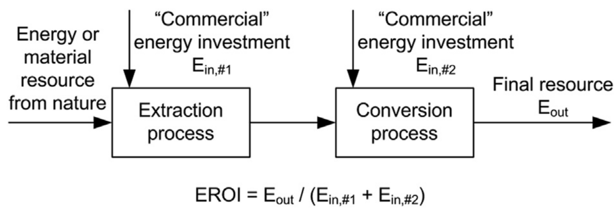


Fig. 1 – Example of Energy Return on Investment (EROI) index calculation.

oil equivalents consumed by the mass of good or service produced.

The EROI is, most of all, concerned with the depletion of fossil energy, therefore all process inputs of material and energy, which do not require the use of fossil equivalent resources, are not accounted for. Services provided for free by the environment (such as soil formation and water) are not accounted for within the EROI framework. Human labor and economic services are also not included in most embodied energy analysis, because it deals with the idea that only fossil energy can be subject to scarcity, while natural resources are unlimited in availability and therefore they should not be accounted for within an energy balance [23].

Hall et al. [16] argue that net energy analysis offers the possibility of a very useful approach for looking at the advantages and disadvantages of a given type of fuel and offers the possibility of looking into the future in a way that economic markets are, seemingly, unable to do. Nevertheless, the authors argue that EROI by itself is an insufficient criterion by which judgments may be made, although it is one of most important, especially when it indicates that one given type of fuel has either a much higher or a lower EROI than others.

In addition to energy analysis, there are other methodologies being used by the scientific community to assess fuel production alternatives. Giampietro et al. [24], for instance, states that MuSIASEM (Multi-scale Integrated Analysis of Societal and Ecosystem Metabolism) should be used to overcome the misunderstanding of a regular EROI calculation. Basically, MuSIASEM takes the "quality" factor of different kinds of energy into consideration and considers the different energy sources separately (Primary Energy Sources, Energy Carriers and Energy End-Uses). Other authors ([25,26]) state that EROI has its importance, but to deeper assess the energy–environmental impacts of any production system, different tools should be used simultaneously (for instance, embodied energy analysis, emergy accounting [27], material flow analysis [28], life cycle assessment [29], among others.), each one with their own rules and meanings, supplying several indicators at different scales.

3. Energy system diagram: importance and meaning

According to Brown [30], the publication of H.T. Odum's book [31] entitled "Environment, Power, and Society" culminated a decade of development of the energetic language, containing explicit definitions, in which the mathematics were illustrated and used extensively to explain in pictures what words often failed to do: to capture the whole systems' energetics and dynamics. In M.T. Brown's article [30] entitled "A picture is worth a thousand words", the paper title itself perfectly expresses the meaning of the energy system diagram. Considering that no system can understand itself, developing simple models that have enough of the characteristics of the original system to resemble reality, but being, at the same time, simple enough to be understood is the way it can approach understanding. In this sense, Odum's energy circuit language [27] is a powerful method for humanity to help the system see and understand itself.

Diagrams of our world can be called energy diagrams because everything has some energy. Pathways may indicate causal interactions, show material cycles, or carry information, but always with some energy. When systems are considered in energy terms, some of the bewildering complexity of our world disappears: situations of many types and sizes turn out to be special cases of relatively few basic types. Energy diagramming helps us consider the great problems of power, pollution, population, food, and war free from our fetters of indoctrination [31].

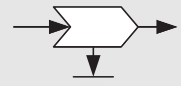
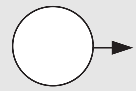
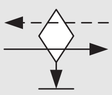
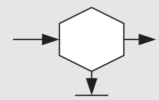
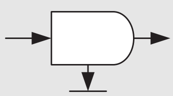
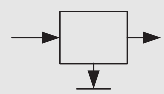
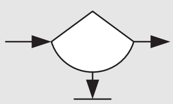
To deeper understand a problem, it is mandatory to understand the way in which the problem is influenced by its surrounding system. Diagramming the whole system under concern is the first step, and for this, a systemic view is essential. The initial diagram can contain in detail all drivers (energy, mass, money, information, etc.) considered important and acting on the system. Whether parts are aggregated or disaggregated, energy systems diagrams should have all the known inputs and outputs of the system crossing the selected window boundaries. Often, diagramming is done by a group of people sharing knowledge in a participative way, usually resulting in a complex diagram. The first complex diagram is a kind of inventory that can be simplified by aggregation, without eliminating any of the important drivers [27].

Drawing an energy diagram starts by defining the window of attention (the system boundaries), enlisting the important external sources and forcing functions, enlisting the main components within the system's boundaries and enlisting the processes (flows, relationships, interactions, production and consumption, etc). These steps can be also made using the conventional symbols of engineering (boxes and arrow lines indicating flows), but using Odum's symbols instead (Table 1) enables the diagram to provide a pictorial description of all processes, driving forces (material and energy flows, free environmental flows, other non-material flows as information), products, recycling patterns, and interactions among components, which are all important aspects of an integrated assessment.

4. Emergy accounting

Emergy accounting was proposed in the 1980s by Odum [32] as a new method for integral evaluation to account for the quality of matter, energy, and information within systems. The classical definition of Emergy is "the available energy of one kind of previously used up directly and indirectly to make a service or product. Its unit is the emjoule" [27]. Emergy Accounting considers every contribution from nature and

Table 1 – Symbols used in energy systems diagram.

Symbol	Meaning	Symbol	Meaning
	Generic resource flow (energy; mass; money, when dotted)		Interaction among flows with different quality
	Dispersion of potential energy into heat		Flow-limited energy or resource input
	Economic transaction: resources (solid) vs. money (dotted)		Generic consumers
	Primary production process (photosynthesis)		Generic process box
	Storage of resources or assets		

Source: Odum [27].

human economy in order to know the relative importance of each resource [32]. According to Odum [27], real wealth can be measured by the work previously done to produce something, thus emergy can be considered as a scientific measure of real wealth in terms of the energy previously required to make something. Fuller description about Emergy methodology can be found in Odum [27], Brown and Ulgiati [33], Ulgiati and Brown [34] and within two important websites: International Society for the Advancement of Emergy Research (www.emergysociety.org) and Center for Environmental Policy of University of Florida (www.emergysystems.org).

Usually, energy is defined as the amount of work that can be performed by a force, based on the physical principle that potential energy is necessary. In accordance to the second law of thermodynamics, each transformation process degrades the available potential energy, but the "quality" of the remaining energy is increased. "Energy quality" is a crucial point related to the Emergy Methodology. Ulgiati and Brown [34] argue that while it is true that all energy can be converted to heat, it is not true that one form of energy is replaceable by another in all situations. For instance, plants cannot substitute fossil fuel for sunlight in photosynthetic production, nor can humans substitute sunlight energy for food or water. The quality that makes an energy flow usable by one set of transformation processes makes it unusable for another set. Thus, quality is related to a form of energy and to its concentration – higher quality is somewhat synonymous with higher concentration of energy and results in greater flexibility. So, wood is more concentrated than detritus, coal is more concentrated than wood, and electricity is more concentrated than coal.

Energy quality is represented in the emergy methodology mainly by two Unit Emergy Values (UEV): transformity (seJ J^{-1}) and specific emergy (seJ g^{-1}). Both consider a "donor-based quality" and use an input/output relationship of the system, but each one uses different units to better explain the flows (for instance, mineral flows are better explained in mass units than energy, while electricity is the opposite). UEV is a conversion factor used to convert different kinds of energy into solar emergy. According to Ulgiati et al. [35], as well as all conversion factors of any methodology, UEVs must be frequently updated and their quality must be double checked to allow good final results. Initiatives in this sense are also discussed in Ingwersen [36], Amponsah and Le Corre [37] and Brown and Ulgiati [38].

Emergy accounting is being applied to assess many different systems, including natural ecosystems [33], agricultural production [39,40], watersheds [41], biofuels [23,42,43], cities [44], countries [45] and so on. For an emergy evaluation, the system under study must first be represented by an energy diagram using the symbols described in Table 1. Subsequently, all raw values of energy and mass flows identified in the diagram are multiplied by their respective UEVs, resulting in flows with the same unit: solar emjoules (seJ) per time (usually a year period). Finally, these flows are used to calculate emergy indices (Fig. 2) and draw conclusions about system performance. A brief description of emergy indices used in this work is given below:

(a) Transformity is defined as "the solar emergy required to make one Joule of a service or a product" [27]. Transformity is an expression of the quality of the output

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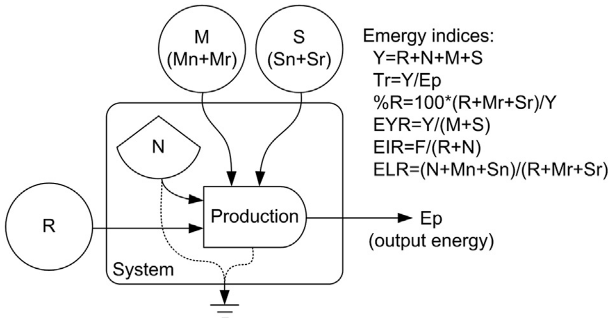

Fig. 2 – Aggregated diagram and emergy indices used in this work. R: natural renewable resources; N: natural non-renewable resources; M: materials from economy; S: Services from economy; Y: total emergy used by system; Tr: transformity; %R: renewability index; EYR: emergy yield ratio; EIR: emergy investment ratio; ELR: environmental loading ratio; "r" and "n" subscript means respectively renewable and non-renewable.

itself, for the higher the transformity, the more emergy is required to make the product flow [46].

(b) Renewability (%R) is the percentage of total renewable emergy used by the system. It ranges from 0 to 100%, where higher values mean higher renewability degrees. According to Brown and Ulgiati [33], in the long run, only processes with high %R are sustainable. Systems dependent of renewable resources reaches a stable steady-state production level and are not directly affected by the storage reduction of non-renewable resources.

(c) Emergy yield ratio (EYR) is a measure of the system's ability to explore and make natural resources available through external economic investment. It reflects the potential contribution of the process to the main economy due to exploitation of local resources [33].

(d) The emergy investment ratio (EIR) measures the intensity of invested emergy from the external economy [33]. It assesses the relationship between the nonrenewable resources from economy and natural resources. Lower EIR values mean more efficiency in economic resource allocation.

(e) Environmental loading ratio (ELR) is an indicator of the pressure on the environment produced by the system and can be considered as a measure of ecosystem stress. According to Brown and Ulgiati [33], ELR values lesser than 2 indicate low impact on the environment, values between 2 and 10 mean moderate impact, and values higher than 10 mean large impact.

5. Case study: embodied energy and emergy evaluation of the Brazilian large-scale sugarcane ethanol production

Before discussing the results of large-scale sugarcane ethanol production, some concepts and definitions must be emphasized:

5.1. *What are negative externalities?*

The global economy of today has been shaped by distorted market prices that do not incorporate environmental and social costs, called externalities [47]. According to Pillet [48], externalities are "consequences that arise from situations in which actions of one agent or group of agents affect the production or well being of others in the economy, especially the welfare of people who are external to that decision. In other words, people who are not fully consenting parties in production decisions, as they are in sales and purchase, are impacted by outputs of production".

Regarding agricultural production, Pretty et al. [49] classify negative externalities as the damages to water, air, soil, biodiversity, landscape, and human health. The same authors state that negative externalities costs in United Kingdom reach a value of 230 \$ ha^{-1} y^{-1} for conventional agricultural production and around 92 \$ ha^{-1} y^{-1} for organics.

If the market price continues to be influenced by supply and demand rules and the concept of product quality continues to be synonymous with usefulness to the human economy instead of synonymous with the total energy used to make it, then the true wealth of a product could never be revealed. Trying to overcome this issue, externalities could be accounted for within the economic assessment of any system, but Pillet [48] argues that including externalities cost (obtained through a willing-to-pay or other conventional economic assessment) within the economic assessment of a system, it will be assigned to the sales price. Thus, society will pay for that cost instead of paying for the production system that caused them. From this logic, the *em*ternality concept was proposed within emergy theory [27], in which "*em*ternalities come to view as the quasi-counterpart of established economic externalities, except that they designate unassessed inflowing environmental contributions instead of unpriced, outflowing impacts of economic process on the environment" [48]. In short, the Emternalities should be considered in any energy assessment, even recognizing that regional studies must be carried out so as to estimate more accurate values.

5.2. *What are environmental services?*

Environmental services are widely recognized as essential to human life, but not considered by the market economy because they are supplied free-of-charge by the biosphere. Examples of environmental services are climate regulation, potable water production, erosion control, pollination, soil formation, and so on [50]. A key work on environmental services (or positive externalities) was published by Costanza et al. [51]. The authors showed that environmental services are valuable for humanity, who have a tendency to ignore those services because they assume them as free and unlimited. The authors used the contingent analysis approach to estimate the value of environmental services for the entire planet, obtaining a total value of 33 T\$ per year (577 \$ ha^{-1} y^{-1} for the marine biome and 804 \$ ha^{-1} y^{-1} for the terrestrial biome).

All land use covers are able to supply environmental services for society, even those considered more urbanized, such as parks within cities. Nevertheless, it is obvious that a land

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occupied entirely by natural vegetation can supply more quantity and diverse kinds of environmental services as compared to a human-dominated system. Thus, a healthy landscape should feature a balance among natural vegetation, agricultural production, and urbanized areas. Brazilian Environmental Law [52] establishes the minimum natural areas that an agricultural landscape must keep – from 20% to 80% of total area depending on the region, hills with high slopes, and buffer on rivers – but it is very difficult to monitor landowner compliance with the law due to the hugeness of the Brazilian territory and the lack of sufficient specialized labor and technology. Additionally, landowners usually use the best soils and water to produce agricultural products within one plot of land, and the law is respected through their acquiring land in other non-agricultural regions and leaving them undeveloped. This results in a non-balanced distribution of natural areas and its impacts on environmental services production and distribution to society (i.e. some regions have large amounts of potable water, climate regulation, etc., while other regions do not). As warned by Metzger et al. [53], worse scenarios could develop, should traditional politicians, opportunistic economic groups, and powerful landowners pressure for changes in the Brazilian environmental law towards reducing the current minimum percentage for natural vegetation protection even further.

Economic evaluation of environmental services will hardly reflect its real wealth; on the other hand, making use of a biophysical approach could be a better alternative. In this sense, accounting for the mass of CO_2 absorbed by vegetal biomass and the volume of water infiltrated into the ground are two important aspects that should be taken into consideration in environmental services assessments, even recognizing that they do not reflect all environmental services and inaccuracy in their conversion factors still remain.

5.3. *Embodied energy analysis of the Brazilian large-scale sugarcane ethanol production*

Fig. 3 is an attempt to show the main differences between a usual embodied energy analysis against an emergy evaluation – for deeper details, see Herendeen [22]. The main process is represented by sugarcane ethanol production (bottom box), which depends on external energy and material resources. Those resources come from other systems, which can be located close to or far away from the ethanol plant – for instance, all steel used in the infrastructure, fertilizers used in sugarcane field, diesel used to operate tractors and harvesters, solar radiation for photosynthesis, rainfall for evapotranspiration, etc. Embodied energy analyses consider some of these resources by accounting for the fossil energy necessary to make them, using energy intensity factors (represented by oil equivalents) as a conversion parameter. On the other hand, emergy evaluation accounts for all of these resources (including resources from nature and economy) by accounting the solar emjoules necessary to make them, using the UEVs as conversion parameters. It is important to highlight that the conversion factors, be those used in embodied energy analysis or those used in emergy evaluation, must be double checked by analysts before being used as they must be up-to-date and reliable to be taken into consideration in any evaluation.

There are enormous policy implications associated with the debate over the net energy [of biofuels] [14], however, although that net energy (and also emergy) calculation is simple in concept, it is difficult in execution. There is no universally agreed or detailed methodology for all approaches. Decisions must be made, case by case, about what is legitimate to include and what can be excluded as an energy input. The purpose of the calculation, therefore, has a large impact on what is included and the final estimate calculated. In the EROI calculation, all environmental inputs, information and labor (some analysts account for labor as metabolic energy spent by workers) are not accounted for because there is no commercial energy involved in their production or maintenance. Thus, embodied energy analysis focuses only on fossil fuel energy sources, considering that only such type of energy is being depleted (i.e. used faster than its own natural replacement time) and disregarding other important energy sources. The issue related to the subjectivity in "what to account for or not" is important, but the energy intensity factors are also essential and they do influence the final results – different conversion factors will provide different results, despite being used for the same raw data. Consequently, a database containing energy intensity factors must be updated and vetted by the energy analyst before use (this also applies to emergy accounting). Moreover, all energy intensity values (and their sources) used in an energy analysis must be put into the document. Without such information, it is impossible to check the calculation procedure and verify if the final numbers do represent the system under study or if they are only a rough average.

Fig. 4 is an attempt to show, in a large-window, all energy and materials involved in the Brazilian large-scale sugarcane ethanol production. Basically, ethanol production depends on environmental services (for instance, rainfall, ground or surface water, erosion control, micro-climate control, plant pathogen control, soil microbial biodiversity, etc.), fertilizers in the sugarcane production, diesel to operate the tractors and harvesters, materials (steel, plastic, rubber, copper, bricks, wood, and so on), workers in both agricultural and industrial phases, and finally information (representing technology, innovation and systemic knowledge; see Ortega [54] and Furtado et al. [15] about this issue). The industrial processes involved in the first generation ethanol production are well known: juice extraction, fermentation and distillation. An important issue is related to by-products (bagasse obtained after sugarcane crushed and vinasse resultant from the distillation process), because until one decade ago, both by-products were considered as an economical and environmental problem of ethanol plants – mainly vinasse which is characterized by high oxygen biochemical demand. Currently, bagasse is burned in boilers within ethanol plants to produce steam and electricity, and most of the vinasse is used in the sugarcane field as a fertilizer.

Bold lines in Fig. 4 represent energy flows (i.e. commercial energy) accounted for a typical embodied energy analysis. It seems clear that, from a systemic point of view, there are many more energy sources involved in the ethanol production that are not considered in an embodied energy analysis procedure, for instance, all natural resources, human-labor and

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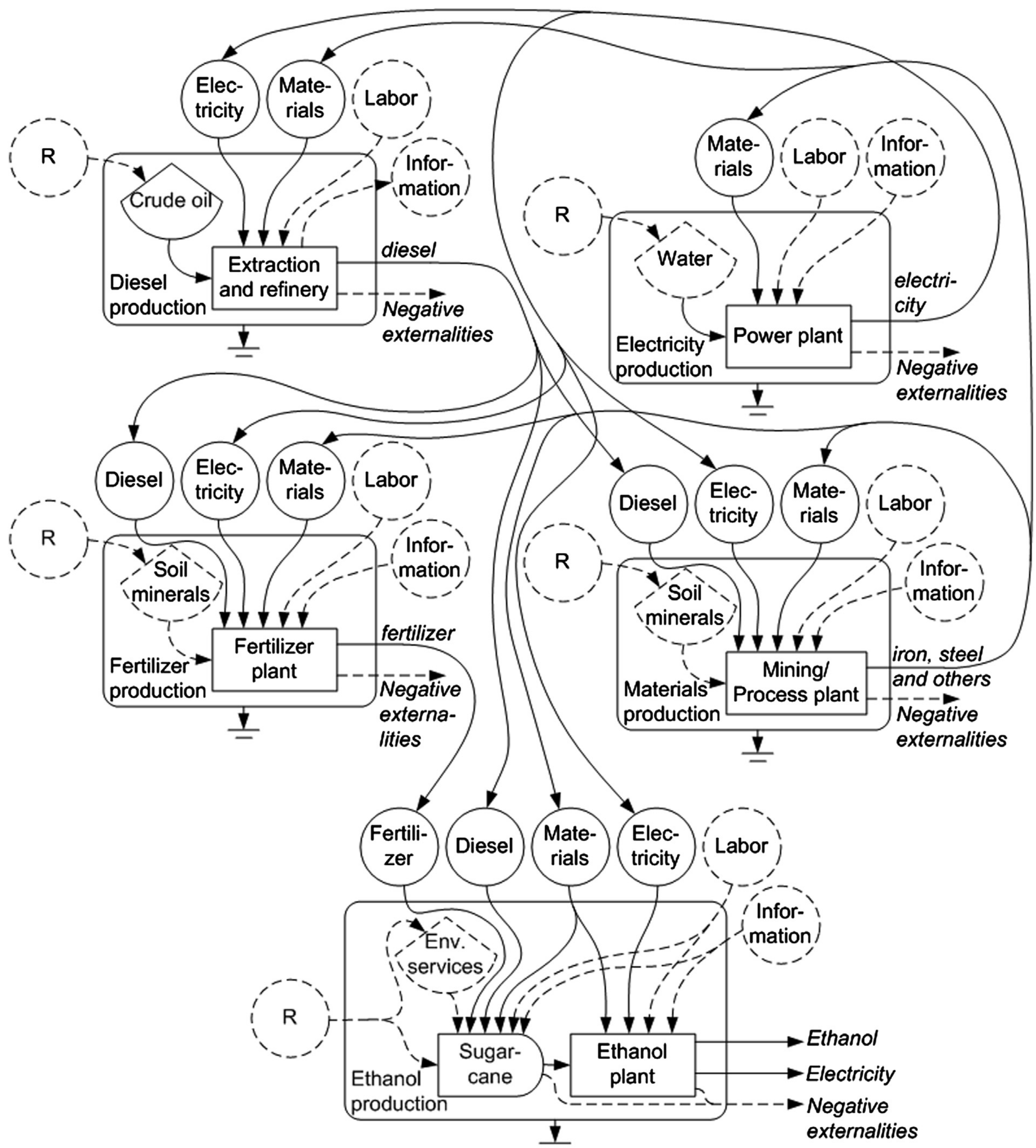

Fig. 3 – Material and energy involved in Brazilian sugarcane large-scale ethanol production. Continuous line represents energy and material flows accounted for embodied energy analysis, while dashed line added to continuous line are accounted for by emergy accounting. R: natural renewable resources; Env. services: environmental services.

services, information, environmental services, and negative externalities are not accounted for.

Technological coefficients for an ethanol plant have changed considerably since the Brazilian Ethanol Program started in the 1970s, primarily due to an exponential increase in the ethanol production–consumption binomial in these last 10 years. Thus, evaluations made through the years obviously show different final indicators. To avoid misunderstandings about what kind of ethanol plant this study focuses on, Table 2 shows its main characteristics. Data correspond to the years 2005–2008 and represent the average values from secondary raw data for forty ethanol plants currently operating in Sao Paulo State [55] and an additional one assessed by Pereira and Ortega [12]. Ethanol plants have large areas taken by sugarcane fields (31,000 ha) and high productivity (87 Mg ha^{-1}; anhydrous ethanol at 86.3 L Mg^{-1} of sugarcane). Due to the lack of data about the average area with natural vegetation within the ethanol production chain, it was

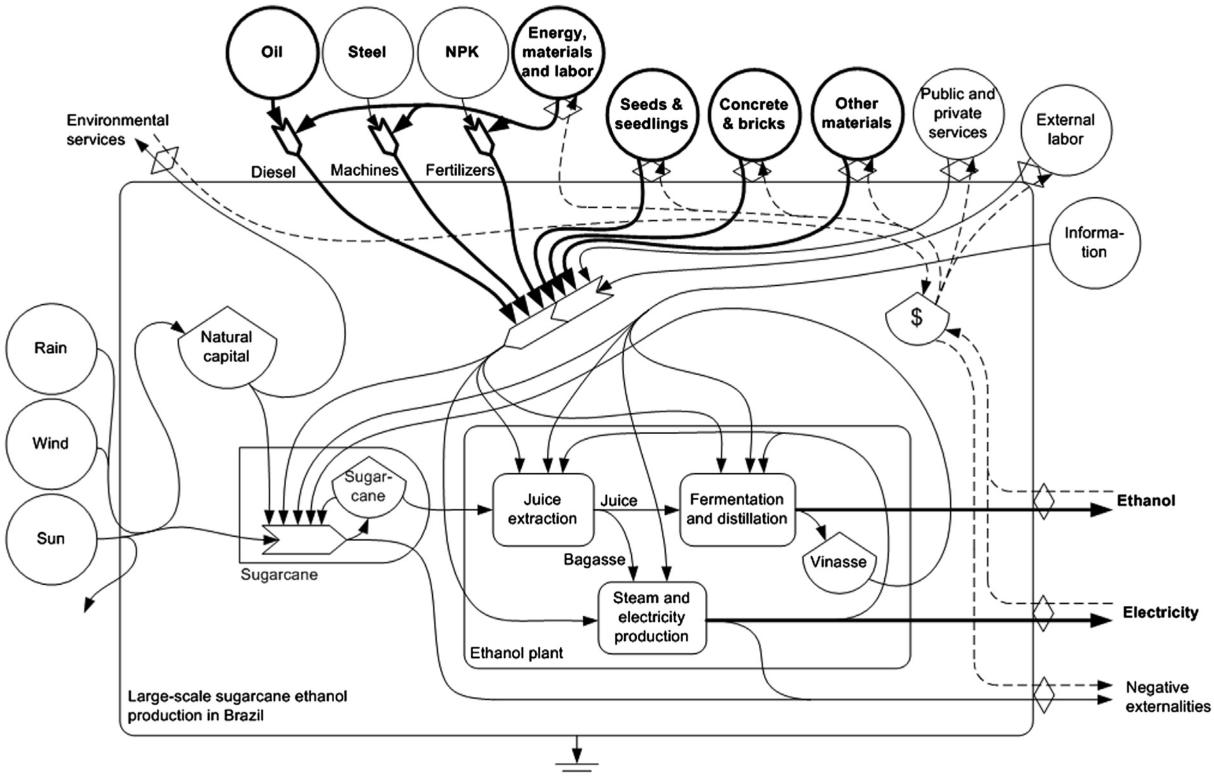

Fig. 4 – Energy systems diagram of Brazilian large-scale sugarcane ethanol production. Bold lines means energy flows accounted for in embodied energy analysis.

assumed that the Brazilian environmental law is respected, by which twenty percent of its total area is taken by natural vegetation – such area is important for environmental services production.

All energy, mass, and monetary inputs are shown in Table 3. The main resources used are, in mass units, water, soil loss, diesel, seedlings, lime and potassium. Regarding outputs, Table 4 shows an ethanol annual production of about 6 m^3 ha^{-1}, and 25 GWh of surplus electricity are sold to the grid.

Raw data in the embodied energy analysis (bold lines in Fig. 4) are multiplied by their respective energy intensity values (Table 3) to result in the total input of commercial energy that goes into the system – such result is also referred to as Gross Energy Requirement (GER). The equivalent oil amount of 31.5 GJ ha^{-1} y^{-1} is consumed in the sugarcane ethanol production, resulting in oil equivalent values of 100 g kg^{-1} of ethanol (which is equivalent to 80 g L^{-1} of ethanol, or 3.37 μg J^{-1} of ethanol). Table 5 shows the EROI calculated for this work (6.7) and by other authors for ethanol production (ranging from 1.38 to 10.6). The differences between EROI values in Table 5 can be explained by the different systems assessed while it is also due to different energy intensities used. A detailed comparison was not carried out here as it is not the objective of this work, but the calculation sheet should be open for verifying firstly whether the energy intensity values are similar among studies and then checking the differences in the amount of flows.

The highest EROI value in Table 5 (10.6) means that each joule of commercial energy used by the system is converted into 10.6 J of another kind of commercial energy. For a simple comparison, the EROI for oil & gas produced in USA have ranged from 100 in 1930 to 11–18 in 2005, indicating that commercial energy is more and more necessary in extracting and transforming crude-oil into oil & gas, supporting the initiative to seek alternative energy sources. At this point, a reader who is not familiarized with the embodied energy analysis may wonder: Could this possibly go against the laws of thermodynamics and create energy? No! It is incorrect to affirm that any system is creating energy. The word "create" must be avoided in any energy analysis. The point is that large amounts of non-commercial energy (but still energy!) such as those from nature and human labor are not accounted for in an embodied energy analysis, which will result in a higher output than input reflected by the EROI index.

Depending on the purposes of the analysis being carried out, it is appropriate to apply embodied energy analysis to verify the dependence on fossil fuel energy sources by the system under study, but the analyst should not overstate conclusions of the energy analysis, i.e. making conclusions that do not belong to embodied energy analysis scope. Thus, when comparing two systems (e.g., sugarcane ethanol production vs. soybean biodiesel), it is incorrect to affirm that

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Table 2 – Main characteristics of large-scale ethanol production considered in this work.

Characteristic	Unit	Ethanol plant[a]
System location	–	Sao Paulo State, Brazil
Time period for raw data	–	2005–2008
Source of secondary raw data	–	40 plants [55]; 1 plant [12]
System total area[b]	ha	38,750
Sugarcane area	ha	31,000
Ethanol production capacity	m^3 day^{-1}	860
Sugarcane productivity (wet)	Mg ha^{-1}	87
Sugarcane area burned before harvesting	%	69
Crushed sugarcane capacity (wet)	Gg day^{-1}	9.96
Ethanol productivity per sugarcane	m^3 Gg^{-1}	86.3
Resultant vinasse per ethanol produced[c]	m^3 m^{-3}	10
Sugarcane bagasse per sugarcane crushed[d]	g kg^{-1}	270
Agricultural management	–	Conventional

[a] Average values from Macedo et al. [55] and Pereira and Ortega [12].
[b] It was not possible to find information about natural vegetation areas. Brazilian Federal laws establish that 20% of total area must be preserved (it is called as Legal Reserve, LR), added to Protecting Permanent Areas (APP, i.e. buffer on rivers and water springs). Thus, in this work it was assumed that total area with preserved natural vegetation corresponds to 20% of total large-scale area.
[c] Vinasse is an ethanol production residue. It is a liquid residue with high concentration of organic matter and nutrients that demands high levels of oxygen to be dissolved. Vinasse is spread in the sugarcane field. According to Smeets et al. [56], values till 300 m^3 ha^{-1} y^{-1} has no negative impacts in soil and underground water; in average, ethanol plants apply 100 m^3 ha^{-1} y^{-1}.
[d] Sugarcane bagasse is the biomass residue from crushed sugarcane. Sugarcane bagasse contains almost 0% of moisture and it is totally burned to produce steam and electricity.

sugarcane ethanol is sustainable or renewable just because its EROI is greater than that for soybean biodiesel. If sugarcane ethanol EROI is greater than soybean biodiesel EROI, it means only that converting energy under this way requires lesser amount of commercial energy. However, one system could be highly dependent on other non-renewable energy sources and also release large amount of pollutants to the environment. These important issues related to system sustainability are not addressed in typical embodied energy analyses.

5.4. *Emergy evaluation of Brazilian large-scale sugarcane ethanol production*

All emergy indices calculated in this work can be seen in Table 6. The differences in emergy indices obtained in this work as compared to those from Pereira and Ortega [12] can be explained mainly by the different unit emergy values used, and also due to some differences in energy and mass input flows.

As previously mentioned, transformity is the solar emergy required to obtain one joule of a service or a product. A transformity expresses system efficiency and output quality, i.e. higher transformities stand for lower system efficiency but high quality of output (and vice-versa). While the EROI index is a ratio of the outputs to the inputs, the transformity is the opposite – an input/output ratio. Additionally, transformity considers all energy provided by the biosphere to produce something, and consequently, the inverse of the transformity value will always be smaller than the EROI value. For instance, a transformity of 63.1 kseJ J^{-1} of sugarcane ethanol means that only 15.8 μJ are converted by each joule invested (i.e. an efficiency of about 0.0016%), while EROI shows a ratio of 6.7 (i.e. 670% more output energy than input energy). For a simple comparison, it is known that only from only 0.1 to 8.0% of total energy from solar radiation is converted by plants during photosynthesis.

The renewability index shows a performance of 19% for sugarcane ethanol. This index represents a ratio between renewable and non-renewable energy used up by the system. Thus, a 19% renewability index can be interpreted as low performance indicating weak sustainability for both medium and long time periods. Some values published for large-scale biofuels renewability are: 31% for Brazilian large-scale sugarcane ethanol [12]; 31% for Brazilian soybean biodiesel [71]; 10% for corn bio-ethanol in USA [33]; 35% for cellulosic ethanol from switchgrass [42]. On the other hand, Brazilian sugarcane ethanol produced in a small scale has a renewability rate of about 54% [10]. Since non-renewable resources (basically derived from petroleum and mineral ores) are the driving forces of current large-scale biofuels production, their availability at low-cost over the years to come will become a great challenge for large-scale ethanol production. Researchers are working to improve ethanol production, in which not only the fermentable sugars but also the total plant biomass will be converted into ethanol and will likely increase productivity and all related energetic-economic aspects – this is called second generation ethanol. Productivity must be increased while simultaneously reducing petroleum and mineral usage in fertilizers, equipment, and infrastructure. Additionally, a zero emission/waste approach through a systemic view must be considered in the new ethanol plant projects, in which not only ethanol is produced, but a series of products derived from biomass (chemical, pharmaceutical, food, and so on). This new technological route is referred to as Biorefineries (see for instance Galembeck [72], Gravitis et al. [73], among others, about this issue).

Considering the previously discussed renewability definition (i.e. when an energy source and/or material is replaced by natural processes and replenished faster than the rate at which it is used), it seems clear that when a system uses large quantities of non-renewable resources, its renewability degree will be lower than that of a system that uses few non-renewable resources. The renewability value is represented by the emergy index of renewability, and hardly ever through EROI, as EROI does not account for all energy and matter involved in the production process. It is worth it to say that a product derived from biomass does not indicate that it is a renewable energy source, a notion that may only be apparent when considering a large-scale view through a systems perspective. Currently, renewability of sugarcane ethanol production is low because biomass production relies heavily on fertilizers, fossil fuels, and minerals. The discourse about

Table 3 – Energy and emergy evaluation of Brazilian sugarcane ethanol.

Note	Item	Input flow amount[a]	Unit ha^{-1} y^{-1}	Embodied energy analysis							Emergy accounting					
				Energy intensity[b]			GER[c]		GER (%)	Renew-able fraction	Emergy intensity[d]			Solar emergy		Solar emergy (%)
				Amount	Unit	Reference	Amount	Unit ha^{-1} y^{-1}			Amount	Unit	Refe-rence	Amount	Unit ha^{-1} y^{-1}	
Local renewable inputs (R)													16.6			
1	Sun	52.60	TJ	–	–	–	–	–	–	1.0	1.00	seJ J^{-1}	[27]	52.60	TseJ	–
2	Rain	70.00	GJ	–	–	–	–	–	–	1.0	31.00	kseJ J^{-1}	[60]	2.17	PseJ	16.3
3	Wind	9.20	GJ	–	–	–	–	–	–	1.0	2.45	kseJ J^{-1}	[60]	22.50	TseJ	–
4	Water	552.00	MJ	–	–	–	–	–	–	1.0	68.90	kseJ J^{-1}	[33]	38.10	TseJ	0.3
Natural non-renewable inputs (N)													10.0			
5	Soil loss	10.80	GJ	–	–	–	–	–	–	0.0	124.00	kseJ J^{-1}	[61]	1.33	PseJ	10.0
Materials from economy (M)						100.0							23.3			
Materials for construction and machines						2.0							0.4			
6	Steel	9.62	kg	1.00	g g^{-1}	[57]	404.00	MJ	1.3	0.0	3.16	TseJ kg^{-1}	[33]	30.40	TseJ	0.2
7	Copper (heat trans.)	48.10	g	1.50	g g^{-1}	[57]	3.03	MJ	<0.0	0.0	3.36	TseJ kg^{-1}	[33]	16.20	TseJ	<0.0
8	Rubber (tractor tire)	2.51	kg	2.04	g g^{-1}	[58]	215.00	MJ	0.7	0.4	7.22	TseJ kg^{-1}	[62]	18.10	TseJ	0.1
9	Concrete	1.14	kg	160	kg g^{-1}	[57]	7.69	MJ	<0.0	0.0	2.27	TseJ kg^{-1}	[63]	2.60	TseJ	<0.0
Materials for operating phase						98.0							22.9			
10	Lime	760.00	kg	2.20	dg g^{-1}	[58]	7.02	GJ	22.3	0.0	1.00	TseJ kg^{-1}	[61]	760.00	TseJ	5.7
11	Nitrogen	76.00	kg	1.44	g g^{-1}	[59]	4.60	GJ	14.6	0.0	6.62	TseJ kg^{-1}	[33]	503.00	TseJ	3.8
12	Phosphorous	42.00	kg	2.60	dg g^{-1}	[59]	459.00	MJ	1.5	0.0	5.62	TseJ kg^{-1}	[33]	236.00	TseJ	1.8
13	Potassium	115.00	kg	1.60	dg g^{-1}	[59]	773.00	MJ	2.5	0.0	1.60	TseJ kg^{-1}	[27]	184.00	TseJ	1.4
14	Diesel	8.18	GJ	1.58	kg J^{-1}	[59]	13.00	GJ	41.2	0.0	111.00	kseJ J^{-1}	[64]	908.00	TseJ	6.8
15	Seedlings	2.80	Mg	3.78	cg g^{-1}	[e]	4.45	GJ	14.1	0.3	141.00	GseJ kg^{-1}	[e]	395.00	TseJ	3.0
16	Herbicides	2.20	kg	5.67	g g^{-1}	[59]	524.00	MJ	1.7	0.0	24.90	TseJ kg^{-1}	[33]	548.00	TseJ	0.4
17	Insecticide	160.00	g	4.74	g g^{-1}	[59]	31.90	MJ	0.1	0.0	24.90	TseJ kg^{-1}	[33]	398.00	TseJ	<0.0
Services (S)													49.9			
18	External labor	86.80	h	–	–	–	–	–	–	0.3	7.21	TseJ h^{-1}	[33]	625.00	TseJ	4.7
19	Services	595.00	$	–	–	–	–	–	–	0.0	10.30	TseJ $$^{-1}$	[65]	6.01	PseJ	45.2
Total						31.50	GJ						13.30	PseJ		
Energy of ethanol annual yield	211.00	GJ	3.55[f]	μg J^{-1}						63.10	kseJ J^{-1}					
Mass of ethanol annual yield	7.11	Mg	1.05[f]	dg g^{-1}						1.87	TseJ kg^{-1}					

[a] See calculation procedure on Appendix.
[b] Mass of equivalent oil per unit of input flow; items from#1 to#5,#18 and#19 are not considered in this methodology.
[c] GER = Gross Energy Requirement. Conversion factor: 1 Mg of equivalent oil = 42 GJ [57].
[d] Emergy intensity values without accounting for labor and services and considering an emergy baseline of 15.83 YseJ y^{-1} from Brown and Ulgiati [33].
[e] Our estimation (see Note#15 on Appendix).
[f] Allocation in energy units.

Table 4 – Outputs from agricultural and industrial phases of large-scale ethanol production in Brazil.

Output	Unit	Amount
Ethanol productivity	$m^3\ ha^{-1}\ y^{-1}$	6
Surplus electricity[a]	$GWh\ y^{-1}$	25
Environmental services		
Water infiltration[b]	$m^3\ ha^{-1}\ y^{-1}$	840
Potential carbon dioxide absorbed[c]	$Mg\ ha^{-1}\ y^{-1}$	6.8

Ethanol density of 800 kg m^{-3} and high heat value of 29.68 MJ kg^{-1}.
[a] Surplus electricity of 9.2 kWh Mg^{-1} sugarcane [55].
[b] Rainfall of 1.4 $m^3\ m^{-2}\ y^{-1}$. Assuming a water balance in which 30% of rainfall is infiltrated into the soil of natural vegetation, represented by Legal Reserve (LR) and Environmental Protection Areas (APP).
[c] The current Brazilian environmental legislation consider that Legal Reserve (LR) and Environmental Protection Areas (APP) (both described in footnote of Table 2) can be used only with the purpose to assure the environmental services production, i.e. current agriculture and/or resource extraction practices are totally forbidden in APP areas, but some of those practices are possible in LR areas if there is a sustainability management contract with Brazilian Institute of Natural Environment and Renewable Natural Resources (IBAMA); that contract is called as "Contrato de Averbação", in which only small family-farms can get it in Sao Paulo State. Thus, those areas with natural vegetation will be able to absorb CO_2 from atmosphere since when vegetation is young until its 50th–100th birthday (it depends on biome). After that, the natural biome is considered balanced and it is no longer able to absorb CO_2 (at least at the same ratio as before). If sustainable use of LR and APP was allowed by Brazilian legislation (i.e. concerning sustainable extraction of old trees to be used in non-burning process of biomass as construction for instance), the net CO_2 absorbed in those areas will increase and will not reach steady-state absorption at medium to long time periods. It was not possible to obtain average values for the age of natural vegetation within systems studied here, so it was not possible to quantify updated values for 2011. Thus, we used the term "potential carbon dioxide absorbed" to represent CO_2 absorption by LR and APP areas "if" a sustainable management in those areas were allowed. For this, a Net Primary Productivity (mass of carbon) for a tropical forest of 925 g $m^{-2}\ y^{-1}$ from Amthor [66] was considered.

the renewability of sugarcane ethanol considering exclusively EROI index and/or raw material source (i.e. biomass) should be used with caution by the scientific community to avoid a misinterpretation by the popular opinion.

Emergy Yield Ratio shows a high dependency on economic resources (EYR of 1.37), i.e. about 73% of total emergy used comes from economic resources. An increase in non-economic oil-based inputs is extremely important because using them will be advantageous in a future scenario of low oil availability. Production systems based on non-renewable resources will not be able to compete with others characterized by low oil dependency and greater contribution from renewable resources. Should we consider an economic view, the studied system is highly potential contributor to the main economy due to the exploitation of local resources. On the other hand, this feature is only positive for a limited economic view, disregarding the deeper sustainability concept. EIR showed that, for each unit of emergy from nature, about 2.73 units of emergy from the economy are necessary. Similarly indicated by EYR, the EIR indicates high dependence on economic resources, reinforcing the need of a production management aiming to increase the system's ability to use local renewable resources with low external investment.

Environmental Loading Ratio shows a moderate load on the environment (ELR of 4.24) caused by ethanol plants. According to Brown and Ulgiati [33], in the absence of investments from outside, the renewable emergy that is locally available would have driven the growth of a mature ecosystem consistent with the constraints imposed by the environment, reaching an ELR of zero. Instead, the non-renewable emergy imported by the system drives a different site development, whose distance from the natural ecosystem can be quantitatively indicated by ELR value of 4.24. Thus, systems with low ELR must be the target, looking for performances closer to natural ones.

More than just indicating the system's overall performance, the emergy accounting tables – as well as the embodied energy methodology, life cycle assessment, and other methodologies – provides information regarding which specific system's input flow has higher influence on the final results. For instance, Table 3 shows that reducing soil loss, limestone, diesel, seedlings, and external services could improve the renewability degree of ethanol fuel. Thus, emergy accounting can be also used as a management tool due to its ability to identify hotspots for further actions for improvement.

Table 5 – Energy Return on Investment (EROI) for Brazilian sugarcane ethanol and USA oil & gas.

Source	EROI	Output considered	Raw data used
Sugarcane ethanol (Brazil)			
This work	6.70	Ethanol and electricity	2005; 2006
Smeets et al. [56]	7.7–10.6	Ethanol and electricity	[a]
Macedo et al. [55]	9.30	Ethanol, bagasse and electricity	2005; 2006
Pereira and Ortega [12]	8.20	Ethanol	2006; 2007; 2008
Oliveira et al. [67]	3.70	Ethanol and electricity	1996; 2003
Pimentel and Patzek [68]	1.38	Ethanol	1995; 1999; 2003; 2004; 2005; 2007
Oil & gas (USA)			
Cleveland [69]	100.0	Oil and Gas	EROI for year 1930
Cleveland et al. [70]	30.0	Oil and Gas	EROI for year 1970
Cleveland [69]	11.0–18.0	Oil and Gas	EROI for year 2005

[a] Based on works published in 2004, 2005 and 2006.

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Table 6 – Emergy indices for Brazilian large-scale ethanol production.

Indices	Unit	This work	Pereira and Ortega [12]
Tr – transformity (with labor and services)	seJ J^{-1}	63,100	48,804
%R – renewability	%	19	31
EYR – emergy yield ratio	–	1.37	1.57
EIR – emergy investment ratio	–	2.73	–
ELR – environmental loading ratio	–	4.24	2.23

6. Conclusions

The complex meaning of renewability can hardly be expressed solely by EROI index, as several aspects cannot be explained by a single linear output/input ratio without a systemic view approach. EROI is concerned with the depletion of fossil energy, disregarding all other types of energy and material the availability of which that will not require commercial energy. In this sense, considering EROI as an index of renewability implies that non-commercial energy from the biosphere is infinitely available. However, such development policy will result in a scenario of non-sustainability because all natural storages of energy and material considered as free are being competed for and needed elsewhere to maintain ecological processes that facilitate human life. The target must be set to increasing EROI, but only with the use of renewable material and energy.

All energy evaluations (including both, embodied energy and emergy methods) are important and can provide biophysical indicators capable of describing system energy performance, but any energy assessment should include (i) all raw data, their sources, and assumptions, (ii) all energy intensity factors and their sources, (iii) an uncertainty analysis must be performed, and (iv) appropriate conclusions drawn from their indices, avoiding general conclusions not shown therein. By following these suggestions, energy and emergy performance indicators can be more appropriately defined for decision makers and society.

Considering all results and discussion of this work, the research question presented in the introduction section (Can EROI and/or CO_2 emission reveal the renewability of large-scale ethanol production?) can take “No” as answer. CO_2 emission accounting is extremely important nowadays due to climate change concerns, but it indicates only one aspect among many other important ones to be considered within discussions about renewable energy sources. Concerning EROI, its importance as an energetic efficiency indicator is widely recognized, but users should not relate EROI to aspects that it cannot explain. Despite all the discussion, ethanol fuel and all other biomass-based fuels emerge as important alternatives to fossil-based fuels in tropical countries, however appropriate scientific approaches must be taken into consideration when assessing the sustainability and renewability of their entire production chain.

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Appendix. Calculation procedure of Table 3.

Note #1 (Sun) – Solar radiation = 5 kWh m^{-2} day^{-1} (www.cresesb.cepel.br); Albedo = 20% [27]; Conversion = (kWh m^{-2} y^{-1}) * (Albedo) * (10,000 m^2 ha^{-1}) * (3.6 MJ kWh^{-1}); Input flow = 52.6 TJ ha^{-1} y^{-1}.

Note#2 (Rain) – Rainfall = 1.4 m^3 m^{-2} y^{-1} (www.sirgh.sp.gov.br); Gibbs free energy = 5 kJ kg^{-1} [27]; Water density = 1.0 Mg m^{-3}; Conversion = (m^3 m^{-2} y^{-1}) * (J kg^{-1}) * (kg m^{-3}) * (10,000 m^2 ha^{-1}); Input flow = 70 GJ ha^{-1} y^{-1}.

Note#3 (Wind) – Air density = 1.3 kg m^{-3}; Average of annual velocity = 4.7 m s^{-1} (www.cptec.inpe.br); Geotropic wind = 2.82 m s^{-1} (assumed as 60% of annual velocity) [39]; Drag coefficient = 0.001; Conversion = (kg m^{-3}) * (m s^{-1})^3 * (0.001) * (10,000 m^2 ha^{-1}) * (31.56 Ms y^{-1}); Input flow = 9.20 GJ ha^{-1} y^{-1}.

Note#4 (Water) – Annual consumption = 4.28 Tg y^{-1} [11]; Water consumption of 18.4 L of water per 1.0 L of ethanol, or 1.6 m^3 water per 1 Mg of crushed sugarcane. It includes only industrial phase, because sugarcane irrigation in Sao Paulo State is used only in special cases due to excellent climate conditions. Gibbs free energy = 5 kJ kg^{-1} [27]; Conversion = (kg y^{-1}) * (J kg^{-1}) * (38,750 ha^{-1}); input flow = 552 MJ ha^{-1} y^{-1}.

Note#5 (Soil loss) – Soil loss = 11.9 Mg ha^{-1} y^{-1} [11]; Organic matter content (O.M.) = 4% [27]; O.M. energy = 22.6 MJ kg^{-1} of O.M. [27]; Conversion = (kg ha^{-1} y^{-1}) * (4%) * (J kg^{-1}); Input flow = 10.8 GJ ha^{-1} y^{-1}.

Note#6 (Steel) – Total steel in equipments = 373 Mg y^{-1} [55]; Conversion = (kg y^{-1}) * (38,750 ha^{-1}); Input flow = 9.62 kg ha^{-1} y^{-1}.

Note#7 (Cooper) – Total cooper in equipments = 1.9 Mg y^{-1} (estimated as 0.5% of total steel); Conversion = (kg y^{-1}) * (38,750 ha^{-1}); Input flow = 48.1 g ha^{-1} y^{-1}.

Note#8 (Rubber) – Total rubber used in tires of agricultural machines = 97.3 Mg y^{-1} [11]; Conversion = (kg y^{-1}) * (38,750 ha^{-1}); Input flow = 2.51 kg ha^{-1} y^{-1}.

Note#9 (Concrete) – Used in industrial building, office, laboratories, repair shops and yards = 44.3 Mg y^{-1} [55]; Conversion = (kg y^{-1}) * (38,750 ha^{-1}); Input flow = 1.14 kg ha^{-1} y^{-1}.

Note#10 (Lime) – Macedo et al. [55] used a value of 1.9 Mg ha^{-1}, but it is not clear if this value is annual or for five years period of sugarcane production. Due to that, it was considered Pereira and Ortega [12] as complementary reference and the following value was adopted: 1.9 Mg ha^{-1} at the first year cut and 1.9 Mg ha^{-1} at the third year cut. Thus, the annual value obtained is 760 kg ha^{-1} y^{-1}.

Note11 (Nitrogen) – Annual consumption = 76 kg ha^{-1} y^{-1} [55].

Note#12 (Phosphorous) – Annual consumption = 42 kg ha^{-1} y^{-1} [55].

Note#13 (Potassium) – Annual consumption = 115 kg ha^{-1} y^{-1} [55].

Note#14 (Diesel) – Annual consumption = 230 L ha^{-1} y^{-1} [52]; Conversion = (L ha^{-1} y^{-1}) * (0.85 kg L^{-1}) * (10,000 kcal kg^{-1}) * (4186 J $kcal^{-1}$); Input flow = 8.18 GJ ha^{-1} y^{-1} or 195 kg ha^{-1} y^{-1}.

Note#15 (Seedlings) – Annual consumption = 2.80 Mg ha^{-1} y^{-1} [12]. To estimate seedlings UEV, a parallel emergy evaluation of seedlings production was made considering a greenhouse area of 1000 m^2 with 70,000 plants y^{-1} produced. Sun (5.26 TJ y^{-1}), steel (500 kg y^{-1}), PVC plastic (4.25 Mg y^{-1}), water for irrigation (25.6 GJ y^{-1}), electricity (3.60 MJ y^{-1}) and soil (organic matter; 70 Mg y^{-1}) were accounted for, resulting in an UEV of 141 GseJ kg^{-1}, without accounting for labor and services. The same procedure was made to estimate the energy intensity, reaching a value for equivalent oil of 37.8 g kg^{-1} of seedlings.

Note#16 (Herbicide) – Annual consumption = 2.20 kg ha^{-1} y^{-1} [55].

Note#17 (Insecticide) – Annual consumption = 160 g ha^{-1} y^{-1} [55].

Note#18 (External labor) – Permanent workers = 986,580 h y^{-1} [11]; Provisory workers = 2,375,100 h y^{-1} [12]; Provisory workers for sugarcane harvest season with 270 workdays y^{-1}. These workers are generally related to several social problems that were not discussed in this present work. Conversion = (h y^{-1}) * (38,750 ha^{-1}); Input flow = 86.8 h ha^{-1} y^{-1}.

Note#19 (Services) – Services = 365 \$ ha^{-1} y^{-1} [12]; Services include taxes, market price of all economic inputs and labor. Emternalities = 230 \$ ha^{-1} y^{-1} [49]; Input flow = 595 \$ ha^{-1} y^{-1}.

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