SUSTAINABILITY ANALYSIS OF BIODIESEL PRODUCTION CHAIN

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Abstract. *The biodiesel fuel production chain is analyzed with respect to its sustainability. The biodiesel considered in this study is an ethyl esther, produced from degummed soybean oil and anhydrous ethyl alcohol, both derived from renewable resources (soybean and sugar cane). The conducted study is based on exergy and emergy analyses, as well as on a methodology that takes into account inputs of resources from the environment and from the economy, as well as the impact of emissions on the environment. The obtained results show that the analyzed biodiesel production system strong depends upon the economic inputs, makes intensive use of non-renewable resources and exhibits modest sustainability index (12%).*

Keywords*: bioodiesel, emergy analysis, exergy analysis, sustainability.*

1. Introduction

A system can be defined as a set of elements that have specific attributes and functions, interacting with each other and with the outside, in order to produce an energy flow, a product or a service [1].

The environment is formed by several ecosystems. Environment conservation demands environmental work, which must be performed by these ecosystems through natural processes (physical, chemical and/or biological) of energy transformation. There are two basic energy sources available for ecosystems: the internal biosphere inventory - water, atmosphere gases, lithosphere solids and the biodiversity reservation (fauna and flora) - and external sourced flows - solar radiation, moon gravity energy and the internal heat of the planet. The environment capacity of keeping its own conservation conditions is, therefore, limited by the energy available and by the ability of natural ecosystems to use and tranform this energy [1, 2, 3].

The increasing environmental degradation generated by economic activities leads to the search for environmentally harmless productive processes, that is, those processes that meet the society needs although without compromising environment conditions [4].

As the productive processes depend upon environment resources and services, the sustainability of an economic system, either agricultural or industrial, is connected to the sustainability of ecological systems, that is, to the production capacity of natural resources and the performance of environmental services necessary to the economic processes and to the environment conservation. Therefore, a methodology aiming at assessing the feasibility of an economic system should, necessarily, take into account the processes carried out by the economic system as well as by the natural systems [5, 6, 7].

2. Exergy analysis

The exergy analysis makes use of the concept of exergy in the assessment of industrial systems. Exergy is defined as the maximum amount of useful work that could theoretically be produced by a system when it interacts with the reference environment to equilibrium [8]. The reference environment adopted in this study is that defined by Szargut et al. [9] with a temperature of 25°C and a pressure of 1atm. Regarding the chemical composition, the reference environment is considered as being constituted by a group of substances whose concentrations reproduce, as much as possible, the natural environment.

Exergy can also be interpreted as a measure of the potential a matter or energy flow has to modify this environment [10]. Exergy can be transferred from one system to another and, differently from energy; it can be destroyed as a result of irreversibilities. Besides exergy destruction, in general, industrial processes also exhibit exergy losses in the form of waste. Thus, the total exergy of a system can diminish due to exergy destruction as well as to exergy loss [4, 10].

Exergy analysis is used in the optimization of industrial processes and consists basically of locating, assessing and reducing exergy destruction and exergy losses in these processes [3, 11]. However, it is convenient to stress that the impact caused by exergy destruction differs from the impact caused by the exergy contained in the waste. Exergy destruction does not have any direct environmental impact. However, high exergy destruction rates in industrial processes are compensated by the system through the increased consumption of exergetic inputs, thus lowering natural resources reserves. In order to decrease the resource use in the processes and, consequently, minimize the environmental impact related to degradation of natural resources, it is necessary to increase the exergetic efficiency of the industrial system [4, 10].

Exergy losses related to emission of industrial waste can harmfully modify the environment, generating the degradation of ecosystems where waste was disposed of [4]. The potential that waste has to damage natural systems can be measured by its exergy. However, it should be highlighted that exergy provides only a measure of potential damage to nature, that is, it is not a measure of the environmental degradation that has already taken place [7]. Therefore, this methodology evaluates which system is less harmful to the environment, although it does not allow us to determine either how or whether the ecological systems involved will be able to stand the pressure imposed by the evaluated system [7].

3. Emergy analysis

Emergy, also called embedded energy, is defined as the amount of available energy of one kind (usually solar) that has to be used up directly or indirectly to make a product or perform a service. The concept of emergy comprises history, time and all of the processes involved in making a product or performing a service by a given system [2, 12].

Every system needs inputs in order to make a product or service, and these inputs can be obtained from nature or from society. In the emergetic theory all of the resources necessary to the operation of a system (money contributions, energy and mass flows, information, human work, among others) are expressed in terms of solar energy using as unit the solar emergy joule (seJ) [2].

The energy conversion factor, used to express all of the flows of a system in terms of emergy is called transformity. Transformity can be defined as the emergy required to produce one Joule of a certain service or product. To make a product or service, a system performs energy transformation processes. At each transformation, a certain amount of energy is used to obtain a smaller amount of another type of energy. The higher the transformity value, the larger amount of solar energy employed in making the product or performing the service. Thus, the transformity value can be obtained by dividing the sum of all inlet emergy flows by the outlet energy flow [2].

In the emergetic methodology, systems and processes are represented through emergy diagrams. For this representation, the flows related to the system are counted, classified and converted into emergy units. The classification of an inlet flow is done according to its source and according to the kind of the resource. Natural resources from local ecosystems are classified as renewable (R) and non-renewable (N). Resources provenient from external economic systems (such as materials, fuels, capital goods, services and workforce) are called purchased feedback (F). From these inlet flows the manufactured product is obtained. This is the yield (Y). These flows can be represented as shown in Fig. 1.

Once the input and output flows are identified and expressed in emergy units, the system is, therefore, evaluated regarding economic and ecological aspects, through several indicators.

Contrary to other theories, the emergy analysis considers environmental products and services. However, the waste disposal into nature is not considered by the emergetic methodology, inhibiting the application of this theory in the analysis of economic systems (agricultural and industrial), since the waste generated by these activities is directly related to the environmental pollution and, therefore, cannot be disregarded in the evaluation of environmental impact of an economic system [3].

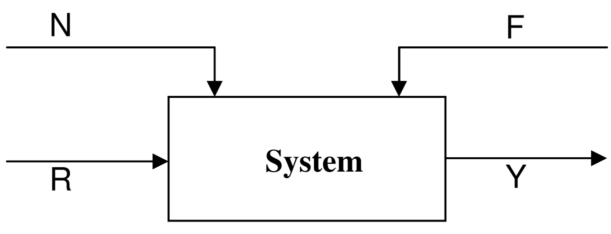

Figure 1. System emergy flows.

4. Integrated methodology of environmental analysis

Taking into account that every productive process causes some kind of harm to the environment, it results evident the complementary character of exergy and emergy methodologies. The integration of both these approaches has as its main objective the development of a broad evaluation methodology to measure and minimize the environmental implications related to the human activities.

The environment acts as both a source and a deposit to the economic systems, because it provides the resources at the same time that it receives the waste generated by those systems. The emergetic analysis considers only the source function, that is, environment as a resource provider for productive systems. On the other hand, the integration of exergetic and emergetic methodologies, as proposed by Bakshi [3] and by Ulgiati and Brown [13], permits to include in the analysis both the provider and the recipient environment functions.

In the application of this integrated methodology, resources, investments and the waste related to the processes that are part of the evaluated system must be converted into a unified measuring unit. As proposed in references [3] and [13], the emergy is used as the unit for flows representation and the transformity (τ) can be used to relate exergy and emergy, as presented in Eq. (1).

$$Em\ [\text{seJ}] = \tau\ [\text{seJ/J}] \times Ex\ [\text{J}] \tag{1}$$

The elements considered in the integrated methodology of environmental analysis of systems are: inlet flows, economic and environmental impact and outlet flows.

4.1. Inlet flows

The inlet flows comprise: renewable natural resources (R1), environmental services aimed at emission dissipation (R2), non-renewable resources (N) and investments from external economic systems (F) [2, 3, 13].

Renewable natural resources (R1) are the natural flows originated from direct solar energy, from moon´s gravitational energy and from the geological cycle energy, besides the products and services of local ecosystems that supply the productive system. [1, 2].

In the environmental services aimed at emissions dissipation (R2) is computed the work carried out by the local natural systems to dissipate pollutants emitted by the analyzed economic system [3, 13].

Non-renewable natural resources (N) comprise natural resources from local natural systems, consumed by the economic system at rates above their replacement rates by the environment [2, 3].

Inputs from external economic systems include the economic resources (F1) — materials, fuels, capital goods, services and workforce — and the economic investment used to decrease, dispose of or recycle pollutants produced by the productive system (F2). It computes everything having a money value that is used by the analyzed productive system. Money values can be converted into emergy units (seJ) through the Emergy/Money Ratio [2].

4.2. Impacts

The impacts of emissions are of two kinds: ecological (R3) and economic (F3). The ecological impact of emissions (R3) evaluates the harm caused to the environment through the loss in exergy stored by the affected ecosystems [3]. From the ecological standpoint, exergy can be interpreted as a measure of the status of a natural system (measure of organization level of an ecosystem). Thus, the decrease of exergy stored by the ecosystem provides a general measure of the environmental impact caused by the pollutants [3].

The substances emitted by the analyzed system may be harmful both to human beings and to the environment. The economic impact of emissions (F3) estimates the costs - in terms of emergy - of the damage caused by pollution to the environment [3].

4.3. Outlet flows

The outlet flow (Y) is the product made by the economic system. The emergy of this product is emergy used in its manufacturing, according to Eq. (2).

$$\text{Y} = \text{R} + \text{N} + \text{F} \tag{2}$$

where, R = maximum[R_1; R_2] and $F = F_1 + F_2$.

4.4. Indexes

Similarly to the methodology of emergetic analysis, the integrated methodology of environmental analysis uses indexes to evaluate the economic systems. Such indexes allow us to compare the contributions of nature and economy to the constitution of a product, besides estimating the sustainability of the economic system and its impact on the environment [3]. The indexes used in this study are presented below:

$$\text{Emergy Yield Ratio} = \text{Y}/(\text{F1} + \text{F2} + \text{F3}) \tag{3}$$

$$\text{Emergy Investment Ratio} = (\text{F1} + \text{F2})/(\text{R} + \text{N}) \tag{4}$$

Emergy Loading Ratio = (F1 + F2 +F3+ N +R3)/R (5)

where, R = maximum [R1;R2].

The emergy yield ratio (EYR) is an indicator of the return of the economic investment made in the system. The emergy investment ratio (EIR) points to the degree of dependence of a system upon economic resources. The emergy loading ratio (ELR) is an indicator of the impact of the system on the environment. The sustainability index can be defined as follows

Sustainability Index = EYR / ELR (6)

5. Application to biodiesel production chain

Biodiesel is a liquid fuel originated from the agro-industrial productive cycle and is produced from renewable biological resources (resources replaced through the growing of vegetables). The biodiesel analyzed in this study is an ethyl esther obtained from soybean oil and anhydrous ethanol by mean of a transesterification reaction.

The integrated methodology of environmental analysis must consider all of the processes involved in the production of biodiesel and, therefore, the entire productive chain must be evaluated. The stages comprised in the biodiesel production system are: ethanol production (agricultural and agro-industrial stages), soybean oil production (agricultural and agro-industrial stages) and soybean ethyl esther production through transesterification (industrial process) [14].

In this analysis of the biodiesel production system, the only impact considered was that related to global warming potential (GWP). The other liquid or solid wastes can be reused by the system or by other economy sectors and, therefore, were considered byproducts and not waste of the system [14].

5.1. Calculation procedure

The ethanol produced from sugar cane involves the agricultural processes of soil preparation, plantation and crop care, burn and harvest. Besides that, the following industrial processes are necessary for ethanol production: sugar cane wash, extraction, juice purification and brewage, and ethanol distillation [14]. Table 1 shows emergy values for ethyl alcohol production [14, 15, 16, 17, 18].

Degummed soybean oil production also involves two stages: the agricultural and the industrial. The emergy data for soybean production used in this analysis are shown in Table 2 [14, 19].

Following Ferres [20], it was assumed that the resources necessary to produce one ton of soybean ethyl esther are: 965 kg of degummed soybean oil, 56 kg of anhydrous ethanol, 14,98 kg of sodium hydroxide, 1250 kg of hot water at 50°C, 706 kg of saturated steam at 120°C and 34,5 kW-h of electric energy. The production costs and the classification of these resources are shown in Tables 3 and 4, respectively.

The emergy evaluation was made based on a production rate of $1{,}30\times10^6$ tons of biodiesel per year. This amount of biodiesel is sufficient to replace 5% of the volumetric diesel fuel consumption in Brazil. The following data were also considered: soybean oil productivity of 0.53 t/ha, ethanol productivity of 5.8×10^3 l/ha, ethanol density of 0.789 kg/l and emergy/money ratio 3.70×10^{12} seJ/US$ [14, 20]. The emergy values resulting from these data are shown in Table 5 (for a production rate of 1.30×10^6 tons of biodiesel per year).

Table 1. Emergy inputs for ethanol production.

Input flow	Emergy [seJ/ha.year]
Renewable resources (R_1)	$1{,}42 \times 10^{15}$
Non- Renewable resources (N)	$2{,}67 \times 10^{15}$
Economy inputs (F_1)	$1{,}03 \times 10^{16}$

Table 2. Emergy inputs for soybean oil production.

Input flow	Emergy [seJ/ha.year]
Renewable resources (R_1)	$1{,}10 \times 10^{15}$
Non - renewable resources (N)	$1{,}73 \times 10^{15}$
Economy inputs (F_1)	$9{,}70 \times 10^{15}$

Table 3. Costs of resources for biodiesel production.

Input	Costs
Catalyzer NaOH	740 US$ / ton NaOH
Water	1.15 US$ / ton biodiesel
Steam	10 US$ / ton vapor
Energy	50.43 US$ / 1000 kW-h
Workforce	1.92 US$ / ton biodiesel
Equipment	10 US$ / ton biodiesel
Other resources	12 US$ / ton biodiesel

Table 4. Classification of the biodiesel input flows.

Input	Type
Soybean oil	R, N, F
Ethanol	R, N, F
Catalyzer NaOH	F
Water	F
Steam	F
Energy	F
Workforce	F
Equipment	F
Other resources	F

Table 5. Emergy inputs for biodiesel production.

Input flow	Emergy [seJ/year]
Renewable resources (R_1)	$2,65 \times 10^{21}$
Non- Renewable resources (N)	$4,20 \times 10^{21}$
Economy inputs (F_1)	$2,35 \times 10^{22}$

In order to evaluate the biodiesel impact in terms of global warming potential (GWP) only those emissions related to biodiesel production were computed (including the agricultural stage up to the distribution stage). The CO_2-equivalent emissions regarding the use of this biofuel (generated during its combustion) are not computed as greenhouse gas effect since an equivalent amount CO_2 is reabsorbed through photosynthesis during the crop growing of the vegetable species used to produce ethanol and soybean oil [14]. The total CO_2-equivalent emissions used in the calculations are 31.31 kg/GJ for biodiesel and 31.98 kg/ GJ for ethanol [14, 16].

The environmental services used in the dissipation of pollutant emissions (R_2) can be calculated from the amount of renewable energy used in the dilution process of these gases. In the case of CO_2-equivalent emissions, it is necessary to assess the mass of air required to disperse the gas emissions until a determined concentration level. In this study, this concentration level correspond to the current average CO_2 concentration in Earth atmosphere ($z_{CO2}= 5.67\times10^{-4}$ kg/kg air) [14]. Air mass can then be calculated through Eq. (7)

$$m_{air}\left[\frac{kg_{air}}{year}\right] = \frac{1}{z_{CO_2}\left[\frac{kg_{CO_2}}{kg_{air}}\right]} \; x \; CO_2eq.\left[\frac{kg_{CO_2}}{year}\right] \tag{7}$$

the R2 vector is determined through the kinetic energy of the air mass employed in the emission dissipation and using the wind transformity

$$R_2\left[\frac{sej}{year}\right] = \left(\frac{m_{air} \; x \; v_{wind}^2}{2}\right)\left[\frac{J}{year}\right] \; x \; \tau_{wind}\left[\frac{sej}{J}\right] \tag{8}$$

The economic impact of emissions (F_3) can be quantified through the estimate of losses, in money values, related to the global warming of the Earth atmosphere. Thus, losses related to the economic impact are estimated around 1.4% of the gross national product of Brazil, resulting in US$ 6.41 x 10^9 (based on data for 2002 year). These losses can be expressed in emergy values through the emergy/money ratio. Doing so, the cost of losses related to the greenhouse effect, in emergy units, is 2.37×10^{22} seJ/year. The transformity of the economic impact from emissions (τ_3) is, therefore, obtained through the division of such cost, in seJ/year, by the total CO_2-eq emitted in Brazil during the period of one year (7.58×10^{11} CO_2eq./year). Finally, the economic impact of emissions (F_3), related to the emissions of a biodiesel production system, is obtained by multiplying transformity τ_3 by the amount of CO_2eq emitted by the biodiesel productive system per year [3, 14]. Table 6 shows the results obtained for F_3 and R_2.

The total exergy of each mass flow crossing the boundaries of the biodiesel production system is obtained adding the chemical exergy to the physical exergy. In order to calculate these exergy components the thermodynamic states and the chemical composition presented by Passos [14] were used. The chemical exergy of fuels was obtained through the equations reported by Morris and Steward [9].

Using mass, energy and exergy balance equations (considering steady state conditions and that the boundaries are at the reference temperature) it was found that the exergy destruction is 1.83×10^6 kJ per ton of produced biodiesel. This corresponds to 4% of the total exergy supplied to the system.

Table 6. Emergy values of F_3 e R_2

Input flow	Emergy [seJ/year]
Environment services needed to dissipate the emissions (R_2)	1.76×10^{16}
Economic impact of emissions (F3)	5.72×10^{19}

6. Results and discussion

The emergy of the produced biodiesel and the obtained indexes that characterize the biodiesel production system are presented in Table 7. The strong dependence upon economic resources can be identified in all of the indexes obtained in this analysis. The EYR index represents the ratio between the total incorporated emergy and the emergy invested by the economy. It can be used to assess the investment return, that is, whether biodiesel provides more energy than the amount invested in it by the economy. In order a production system be feasible, its emergy yield ratio must satisfy EYR>1. The resulting value EYR = 1.29 features the high dependence of the biodiesel production system upon the economic inputs.

The values obtained for the emergy investment ratio (EIR) and for emergy loading ratio (ELR) also reflect the high dependence upon economic resources in the biodiesel productive system. The EIR indicates the ratio between economy investments and environmental contributions, that is, the amount of energy employed by the economy to explore a unit of local resource (renewable and non-renewable). A low value for EIR suggests a little use of economic resources by the system regarding the environmental contributions. As the latter are for free, the lower the value for EIR the more competitive the system.

A high ELR, as that obtained for the biodiesel production system, indicates a high technological level in the emergy use and/or a high level of environmental stress (intensive use of non-renewable resources). The more extensive the use of non-renewable resources, both external (F) and local (N), the higher the risk of making energetic resources unavailable for future generations.

The sustainability of the biodiesel production system presented a modest value (12%), verifying a high economic investment and an intensive use of non-renewable resources (local and external) in the production of this biofuel.

Table 7. Results

Item	Value
Product (Y)	3.04×10^{22} seJ/year
Transformity (τ = Em/Ex)	5.85×10^5 seJ/J
Emergy Yield Ratio (EYR)	1.29
Emergy Investment Ratio (EIR)	3.44
Emergy Loading Ratio (ELR)	10.50
Sustainability Index	12%

7. Conclusions

Through the application of the integrated emergy/exergy methodology to the soybean ethyl esther production system it was possible to determine the origin, nature and amount of energy spent in the production of this biofuel, as well as to identify the pressure exerted by the system over the environment. The obtained results show that the analyzed biodiesel production system strong depends upon the economic inputs, makes intensive use of non-renewable resources and exhibits modest sustainability index (12%).

8. References

[1] ORTEGA E. **Engenharia Ecológica: conceitos básicos e importância do trabalho de H. T. Odum.** Available in: <http://www.fea.unicamp.br/ docentes/ortega/livro/C01-Eng.Ecol.pdf>. Accessed in: 05 nov. 2003.

[2] ODUM, H. T. **Environmental Accounting: Emergy and Environmental Decision Making**. New York: John Wiley & Sons, 1996.

[3] BAKSHI, R. B. A thermodynamic framework for ecologically conscious process systems engineering. **Computers & Chemical Engineering**, v.26, p.269-282, 2002.

[4] ROSEN, M. A. & DINCER, I. Exergy as the confluence of energy, environment and sustainable development. **Exergy, an International Journal**, v.1, p.3-13, 2001.

[5] DALY, H. E. Toward some operational principles of sustainable development. **Ecological Economics**, v.2, p.1-6, 1990.

[6] WALL, G. & GONG, M. On exergy and sustainable development – Part 2: Indicators and methods. **Exergy, an International Journal**, v.1, n.4, p.217-213, 2001.

[7] SEAGER, T. P. & THEIS, T. L. A uniform definition and quantitative basis for industrial ecology. **Journal of Cleaner Production**, v.10, p.225-235, 2002.

[8] MORAN, M. J. & SHAPIRO, H. N. **Princípios de Termodinâmica para Engenharia**. 4.ed. Rio de Janeiro: LTC, 2002. Cap.7 e 13.

[9] SZARGUT, J.; MORRIS, D. R. & STEWARD, F. R. **Exergy analisys of thermal, chemical, and metallurgical processes**. Hemisphere, New York, 1988. Cap. 1 e 3.

[10] WALL, G. & GONG, M. On exergy and sustainable development – Part1: Conditions and concepts. **Exergy, an International Journal**, v.1, n.3, p.128-145, 2001.

[11] VALERO, A. **Termoeconomics as a conceptual basis for energy ecological analysis.** Centre for Research of Energy Resources and Consumption (CIRCE) – University of Zaragoza. Available in: <http://circe.cps.unizar.es.>.

[12] BASTIANONI, S. & MARCHETTINI, N. Emergy/exergy ratio as a measure of the level of organization of systems. **Ecological Modelling**, v.99, p.33-40, 1997.

[13] ULGIATI, S. & BROWN, M. T. Quantifying the environmental support for dilution and abatement of process emissions. The case of electricity production. **Journal of Cleaner Production**, v.10, p.335-348, 2002.

[14] PASSOS, M. **Avaliação de Sustentabilidade aplicada ao Biodiesel.** Curitiba, 2004. 111f. Dissertação (Mestrado em Engenharia Mecânica) – Departamento de Engenharia Mecânica, Pontifícia Universidade Católica do Paraná.

[15] MACEDO, I. de C. Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil (1996). **Biomass and Bioenergy**, v.14, p.77-81, 1998.

[16] BASTIANONI, S. & MARCHETTINI, N. Ethanol production from biomass: analysis of process efficiency and sustainability. **Biomass and Bioenergy**, v.11, p.411-418, 1996.

[17] COELHO, O.; ORTEGA E. & COMAR, V. **Balanço de Emergia do Brasil.** Available in: <http://www.fea.unicamp.br/docentes/ortega/livro/C05-Brasil-COC.pdf>. Accessed in: 05 nov. 2003.

[18] ORTEGA, E. **Tabela de Transformidades.** Revisão 2002. Available in: <http://www.unicamp.br/fea/ortega/curso/transformid.htm> Accessed in: 19 fev. 2003.

[19] ORTEGA E. & MILLER M. **Avaliação ecossistêmica – emergética de processos agrícolas e agroindustriais.** Estudo de caso: a produção da soja. Available in:<http://www.fea.unicamp.br/docentes/ortega/livro/C13-Soja_PA.pdf>. Accessed in: 05 nov. 2003.

[20] FERRES, J. D. Viabilidade da produção do biodiesel no Brasil empregando óleo de soja. In: **Congresso Internacional de Biodiesel**, 1., 2003, Ribeirão Preto. Palestra. 2 CD-ROM.

[21] VALERO, A. & LOZANO, M. A. **Curso de Termoeconomía.** Departamento de Ingeniería Mecânica. Universidad de Zaragosa. Julio, 1994. p. 38-39.

9. Responsibility notice

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