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Use of Environmental and Thermodynamic Indicators to Assess the Performance of an Integrated Process for Ethanol Production

Alex R. Nogueira[1], Ana C. G. Donke[1], Marilia I. S. F. Matsuura[2], Patricia H. L. S. Matai & Luiz Kulay[1]

[1] Polytechnic School, University of Sao Paulo, Sao Paulo, Brazil

[2] Brazilian Agricultural Research Corporation – EMBRAPA, Jaguariuna, Brazil

Correspondence: Luiz Kulay, Chemical Engineering Department, Polytechnic School, University of Sao Paulo, Sao Paulo, SP, Avenida Prof. Luciano Gualberto, tr. 3, 380, CEP 05508-900, Brazil. Tel: 55-113-091-2233. E-mail: luiz.kulay@usp.br

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Abstract

Corn is one of the possibilities for diversification of Brazilian ethanol production. Four scenarios of analysis were established. The environmental dimension was evaluated by the Life Cycle Assessment (LCA) approach, whereas the Thermodynamic performance was verified by applying the techniques of Cumulative Energy Demand (CED) and Cumulative Exergy Demand (CExD). The production of ethanol from corn using wood chips for energy supply of the plant resulted in a homogeneous environmental performance. Factors such direct seeding – and the LHV of the wood for energy support this result. For both Thermodynamic analysis the production of sugarcane ethanol had better indexes because the use of bagasse replaced other sources of primary energy. This result remained for a combined analysis between the two dimensions, which related environmental effects in terms of Climate Change with the aggregation of primary energy consumption for ideal systems.

Keywords: ethanol from corn, integrated plant, environmental analysis, thermodynamic analysis, LCA, Brazilian ethanol

1. Introduction

Modern society is deeply dependent on fossil fuels to meet their daily needs. Crude oil derivatives are finite and thus, have become more costly and difficult to find. This paradigm little auspicious motivates researchers to explore and make operational, some alternative sources of energy such as solar, wind, nuclear power, that derived from ocean tides and geothermal.

Biofuels are also included among the potential solutions to be considered to manage, or at least to mitigate, the occurrence of an energy crisis in the future. Successful results achieved in many countries with biodiesel and ethanol from different sources, as well as developments to obtaining other derivatives – biokerosene, biofuels from lignocellulosic biomass, renewable gasoline, and solid biofuels – can endorse this option in terms of effectiveness.

Brazilian ethanol plays an important role in this scenario. Brazilian ethanol has an important role in this scenario to support the internal market for light vehicles. Its production is mainly from sugar cane, which grows in the South Central region of the country. However, as sugarcane also provides the domestic and foreign markets of sugar both segments are frequently exposed to economic instability.

In order to avoid conflicts and get rid of market dependence, companies from the fuel sector invested on alternative agricultural raw materials. One of the possibilities for diversification of Brazilian ethanol production is the use of corn. The solution is suitable for the Northern region of the country, whose high agricultural productivity of recent years has generated surplus production of cereals that are remunerated at low prices for food segment. Furthermore, although still far from being a trivial practice in Brazil the technology that integrates in a single industrial plant the production of ethanol from corn and sugarcane - also cultivated in the region in economic scale - is dominated. These circumstances led to the creation of a pool of distilleries in the State of Mato Grosso with the potential to produce over 250,000 m^3 ethanol / year.

The initiative has been preparing to supply international markets and therefore, apart from a competitive economic performance, the product must demonstrates satisfactory technical and environmental results. This status will be achieved through agricultural practices that are less harmful to the environment and balanced industrial processes, which are also energy efficient.

Due to their adherence, environmental and Thermodynamic analyses can be combined in order to provide accurate evaluations of performance of fuels and energy systems and to identify improvement opportunities (Romero & Linares, 2014). A usual application for this approach concerns the multi-objective optimization, which is carried on to establish the best set of operation parameters for a power system (Buchgeister, 2010; Ahmadi et al., 2011; Pellegrini & Oliveira Jr, 2011; Petrakopoulou et al., 2012; Aminyavari et al., 2014; Manesh et al., 2014; Shirazi et al., 2014). Optimization models are applied to restricted control volumes, comprising only the components of the unit under study. Therefore, the environmental assessment is limited to the quantification of resource consumption, and gas emissions, without assessing the magnitude of the impacts caused by them, and only within that domain.

Environmental and Thermodynamic indicators have also been successfully applied in diagnostic assessments (De Meester et al., 2009; Meyer et al., 2009; Grubb & Bakshi, 2011; Liao et al., 2011; Boyano et al., 2012; Ozbilen et al., 2012; Peiró et al., 2012; Restrepo et al., 2012; Iribarren et al., 2014). Although models formulated according to this approach tend to be less rigorous from the thermodynamic point of view, the environmental aspects are considered from a life cycle perspective. Thus, these assessments allow identifying opportunities to improvement technical and environmental performance of energy systems.

A corollary to this procedure consists in comparing, or even classify, alternatives of potential performance gain for energy systems, according to their conducts in terms of energy use and consequences to the surroundings (Banerjee & Tierney, 2011; Koroneos & Tsarouhis, 2012; Moya et al., 2013; Iribarren et al., 2013; Velásquez et al., 2013; Abusoglu & Sedeeq, 2014). The proposal is useful to support decision-making processes exercised in industrial complexes that, for different reasons, ought to be operated according to the perspectives of cleaner production and loss prevention, as regards to the selection of technological alternatives.

The same methodological approach was applied in this study with the objective of carrying out a diagnosis of the Environmental and Thermodynamic performances for the production of ethanol from sugarcane and corn in an integrated autonomous distillery, located at Mato Grosso State in Brazil. It is expected that the results of these evaluations could contribute to guide management processes of the company and to better define their operating philosophies in order to make its product more competitive in foreign market.

2. Life Cycle Modelling

A typical modeling the processing ethanol from both sugarcane and corn, developed according to technological and operational procedures practiced in the State of Mato Grosso is depicted in Figures 1 and 2. The process can divided in three steps: agricultural production, industrial production and energy cogeneration.

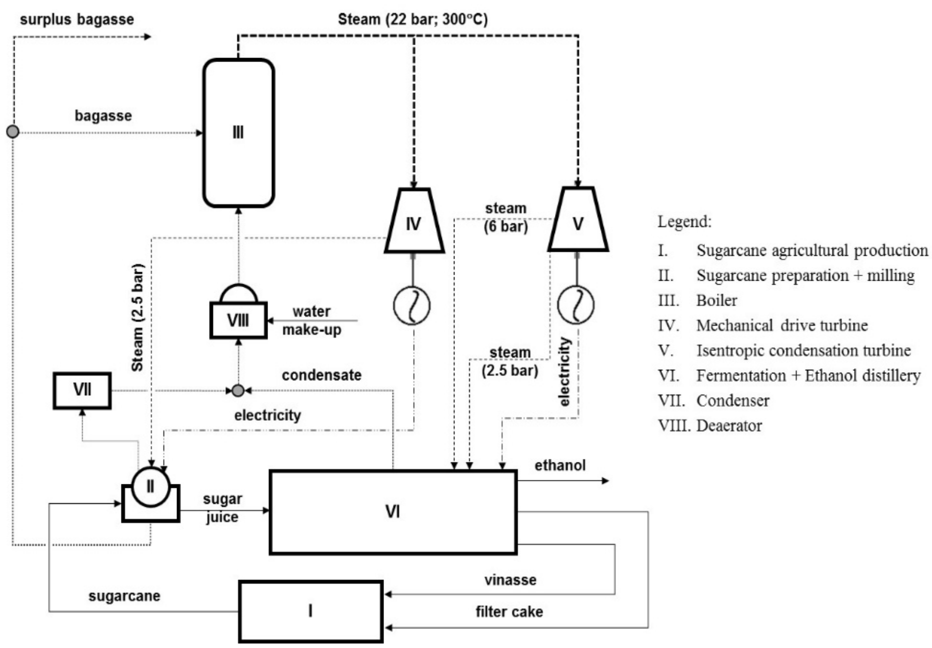

Figure 1. Schematic representation of the production of ethanol from sugarcane

2.1 Agricultural Process

The crops of sugarcane and corn are concentrated in the municipalities of Campos de Júlio (*13° 53′ 56″ S, 59° 08′ 52″ W*), Sapezal (*13° 32′ 33″ S, 58° 48′ 51″ W*) and Campo Novo do Parecis (*13° 40′ 30″ S, 57° 53′ 31″ W*) in the state of Mato Grosso. Sugarcane is cultivated in tropical and humid climate and sandy-clayey soils of low fertility. The area under cultivation has undergone expansion of 26.4% from 2012 to 2013. Native vegetation biome Brazilian Savanah was converted into arable land. The agricultural productivity in the period was 81.7t/ha and there is only one harvest per year. Gypsum, limestone, urea, triple superphosphate, potassium chloride, and herbicides are applied during soil tillage. The variety planted in the region is RB867515. Occurs every year fertigation of 23-25% of the crop area with diluted vinasse that is collected in the industrial process. Mechanical harvesting was applied on 25% of agricultural production in 2013; this procedure reduced the burning straw to about 85,500 t. Activities of tillage, planting and cultivation, and harvesting amounted consumptions of diesel, respectively of 15 L/ha, 2.0 L/ha and 60 L/ha. Spraying herbicides occurs by air and consumes 2.0 L/ha ethanol.

Corn production occurs in similar external conditions. However, this process is carried out under a crop rotation with soybeans. The expansion of crops cultivation area in 2012-2013 was 3.47% and occurred on arable land. Agricultural productivity in the period was 7.5 t/ha. The corn planting is performed by direct seeding with the addition of lime to correct soil acidity. About 10-14 kg/ha seeds and different NPK formulations are consumed in the operation. The harvest is mechanized and keeps the straw in the field. Consumption of diesel for soil tillage, planting and cultivation, and harvesting correspond to 5.0 L/ha, 19 L/h and 11 L/ha.

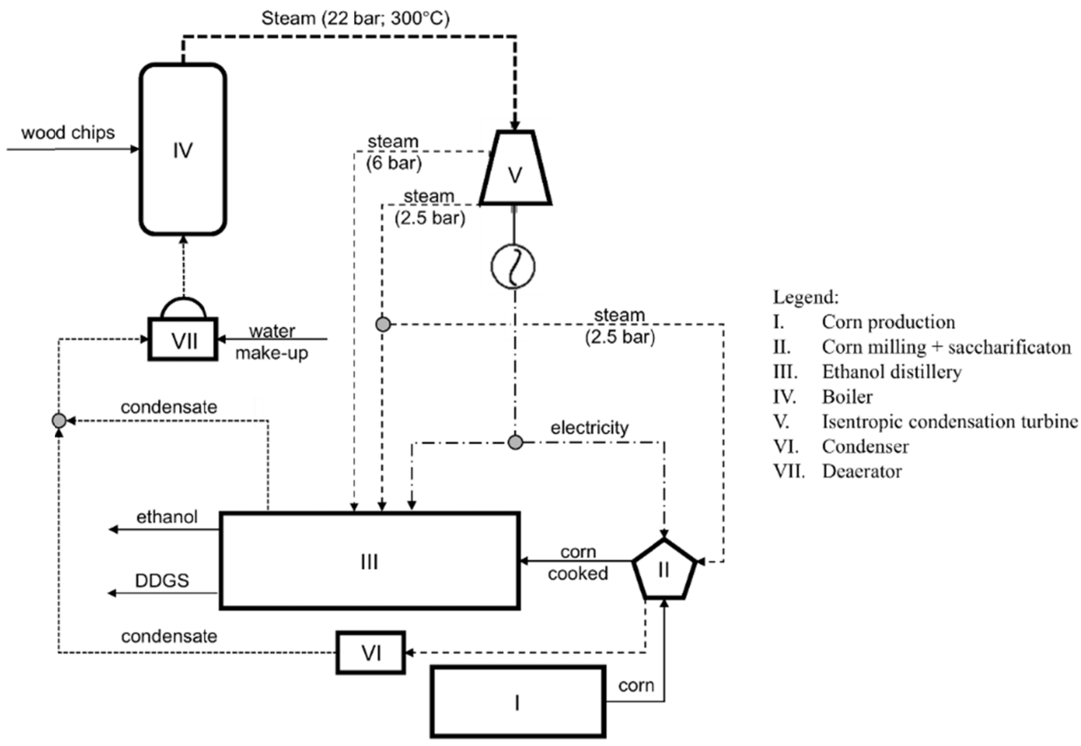

Figure 2. Schematic representation of the production of ethanol from corn

2.2 Industrial Process

In the harvest of 2012-2013 it were produced 60,760 m^3 of ethanol from the milling of 787,000 t sugarcane. The process starts by washing the cane for removal land loaded during harvest, mainly manual. The amount of water that circulates in the operation is significant (~ 4,000 m^3/t sugarcane) but the average rate of make-up is 0.40 m^3/t_{sc}. Sugarcane is chopped and shredded before going to the grind. The juice extraction occurs by wet route (imbibing of 46%) and generates two products: bagasse and sugarcane juice.

The bagasse serves as fuel for meeting energy demands of the unit, and the juice will be prepared for fermentation. This treatment originate the filter cake, which return to the field as fertilizer, and the clarified juice.The juice is concentrated and mixed with yeast milk in order to compose the mash. The water evaporated from the concentration process – exhaust steam – is used in heating the mixed juice and in the distillation. Fermentation is an exothermic process that occurs from the action of *Saccharomyces cerevisiae* on the mash, from which 45–50 $kgCO_2$/t fed material are emitted. The product of this step - wine - is distilled by direct contact with low vapor pressure to obtain hydrate ethanol (95$\%_{ww}$), vinasse and fusel oil. Vinasse is mixed with wastewater from the scrubber, which already contains ashes, and goes to fertigation.

Corn is a starchy raw material and thus predispose a stage of enzymatic hydrolysis prior to fermentation. The ground corn receives water and *α-amylase* enzymes that transform molecules of starch into dextrin. The solution gets another enzyme – *glucoamylase* – that converts dextrin to glucose. During fermentation *S. cerevisiae* produces ethanol from the single sugars. The steps of preparation and fermentation of corn consume 41% of the electricity of the unit. The wine goes to distillation, from which originate hydrated ethanol; vinasse, for fertigation; fusel oil, for chemical segment; corn oil, for food market; and Dried Distillers Grains (DDG), marketed as livestock food supplement, after drying with hot air generated by burning wood chips. The main parameters considered in the modeling of ethanol production from sugarcane and corn are indicated in Table 1.

Table 1. Operational parameters adopted in simulation of ethanol production processes

Raw Material	Parameters		Value (/ton raw material)
Sugarcane	Sugarcane composition	Suspended solids (POL, %)	17.2
		Sugar content (Brix, %)	14.6
		Fibers (%)	12.6
	Operation days (85% efficiency)		218
	Hydrate ethanol production (95%ww) (L)		77.2
	Vinasse (sol.) (ton)		1.80
	Filter cake (ton)		0.042
	Water consumption (ton)		1.65
	Bagasse content (ton)		0.262
	Surplus bagasse (ton)		16.2
	Electric power demand (kW)		16
Corn	Operation days (76% efficiency)		93
	Hydrate ethanol production (95%ww) (L)		370.9
	DDG production (ton)		0.22
	Vinasse (sol.) (ton)		2.77
	Corn oil (ton)		0.020
	Water consumption (ton)		5.20
	Electric power demand (kW)		69

2.3 Cogeneration System

All energy consumed in the process is produced in the distillery process. Thermal energy comes from the burning of biomass – bagasse or wood chips, used in the processing of corn. Electricity is obtained by cogeneration with steam by Rankine cycle. The main operating parameters for modeling the cogeneration system are depicted in Table 2.

Table 2. Operational parameters adopted for the simulation of Rankine cycle

Parameter	Value
Moisture of bagasse (%)	44.91
Lower Heating Value (kJ/kg bagasse)	8,605
Moisture of wood chips (%)	28.60
Lower Heating Value (kJ/kg wood chips)	14,400
First law efficiency of boiler (%)	72 – 77
Isentropic efficiency of condensation turbine (%)	70
Isentropic efficiency of mechanical drive turbine, sugarcane milling (%)	55
Efficiency of the electrical generator (%)	98
Steam pressure (extraction/exhausting/condensation) (bar)	20/1.5/0.8
High Pressure steam consumption (kg/kg sugarcane)	0.54
Low Pressure steam consumption (kg/kg sugarcane)	0.36
High Pressure steam consumption (kg/kg corn)	1.13
Low Pressure steam consumption (kg/kg corn)	2.21
Boiler blowdown (%)	2.2 – 2.7

The boiler produces superheated steam (20bar, 300°C) in amount enough to meet demands of the process. After providing the energy that was carrying the steam (1.5bar, 130°C) goes to deaerator and the cooling tower. Part of this fluid is also used in the pre-evaporator of juice. Cooling tower presents the highest water consumptions of the whole unit ($0.45t/t_{sc}$ and $2.45t/t_c$) due to the replacement of evaporative losses. The superheated steam boosts a turbine, which drives two electric power generators with capacity of 1200kW and 3000kW. During the production of ethanol from corn, just higher capacity unit is in use.

3. Methodology

The approach defined in order to accomplish this analysis comprised the direct comparison of the environmental and Thermodynamic performances for different possibilities of agricultural inputs, and alternatives of fuels to electric and thermal energy generation for the production of hydrate ethanol.

In terms of methodology the study was structured in three steps: a) Establishment of realistic – or at least feasibly – scenarios for operation of the process, with regard to the volume and availability of inputs that are considered by them; b) Development of computational models in order to determine Environmental and Thermodynamic performance indicators for each scenario; c) Evaluation of results.

3.1 Scenarios of Analysis

The procedure for scenarios defining admitted as assumption an annual production of 56,000 m^3 of hydrate ethanol. Four possibilities were identified in conditions of meet that requirement. The options are summarized in Table 3. Scenarios S1 – S3 are supported by the productive capacity of the complex. The S4 scenario evaluates a viable possibility in terms of technology and availability of features that, however, has not been implemented yet.

In scenario S1, the ethanol production occurs entirely from corn processing. In this case, the energy requirements of the unit are met by burning wood chips purchased from regional suppliers. S2 evaluates a similar situation, in which it uses sugarcane as an agricultural input. The thermal and electrical requirements are supply by burning part of the bagasse generated in the grinding step. The surplus biomass is marketed with agricultural producers in the region, in accordance to a regular practice of the company.

Table 3. Alternatives scenarios for ethanol production in the integrated plant

Scenario	Description
S1	Ethanol from corn + cogeneration system driven by burning of wood chips
S2	Ethanol from sugarcane + cogeneration system driven by burning of sugarcane bagasse
S3	Integrated production of Ethanol: corn + sugarcane + cogeneration system driven by burning of sugarcane bagasse
S4	Ethanol from corn + cogeneration system driven by burning of Natural gas

In the S3 scenario, the annual production is achieved from consecutive processing of sugarcane and corn. The amounts of ethanol generated from each raw material were designed so that the industrial complex remained in operation during the manufacturing of corn ethanol, only with surplus bagasse generated during the sugarcane, processing that precedes it. S4 scenario was observed in the context of future perspective. The company seeks an alternative that makes it independent of suppliers of wood for energy. In addition, there is provision for extending the Lateral Cuiaba pipeline, a branch of Brazil–Bolivia gas pipeline to municipalities near the plant. The orientation and layout of the new section, makes natural gas a technically accessible energy source for the unit.

3.2 Elaboration of Models and Performance Indicators

Logic models created to depict Environmental and Thermodynamic performance of the scenarios under study were prepared according to a systemic perspective from 'cradle-to-gate'. Thus, the approach disregards environmental impacts and energy losses associated with post-production steps that also take part of the life cycle of the fuel. The technological characterization of scenarios occurred mainly from primary data, which were collected during four technical visits carried out to the cultivation zones and the integrated plant along the period 2012-2013. Part of them are presented in Tables 1 and 2.

The exception occurred for S4, in which secondary data were used due to its prospective character. Secondary data were also employed to describe consumptions and emissions associated to inputs and capital goods supplementary to the processes. The same occurred for the road transport operation with regard to the selection of capabilities in vehicles. However, the shifting distance were determined by actual data. A Sensitivity Analysis performed on the models revealed that the substitutions had no significant effect on the results of the evaluation.

Data collection occurred only for periods in which the operational behavior of the unit had reached an hourly performance, equivalent with the annual production established to the study – 56,000 m^3 ethanol – in order to minimize the propagation of scale errors. Any positive and negative oscillations of up to 5% in the manufactured volume were admitted in the sampling process, because it did not influenced results.

The type of performance indicators to be used in the study was determining for the selection of techniques for verification of Environmental and Thermodynamic performances of the scenarios. In addition to producing diagnoses of systemic amplitude, that could express these dimensions according to distinct (but complementary) approaches, these methodologies should be able to express the results as specific values (/ m^3 ethanol).

The Environmental performance was established by applying the technique of Life Cycle Assessment (LCA) in compliance with guidelines of the standards ISO 14040 and 14044 (ISO 2006a, 2006b). For the accomplishment of analysis, it was defined as Reference Flow: '*produce 1.0m^3 of hydrate ethanol in an autonomous distillery*'. The 'product system' comprises the agricultural stages - production of cane sugar, corn, and wood chips for energy - and industrial transformations – sugarcane crushing, corn milling and saccharification, fermentation, and distillation of ethanol. Units and equipments from the Rankine cycle of cogeneration – boiler, turbine, electric generators, pumps, deaerator and cooling tower – and, the transportation of inputs are also part of this scope.

The operations of extraction and refining of natural gas in the fields of the San Alberto and Sabalo (BO), and its transportation through the Lateral Cuiaba pipeline (1436km and 1559km) to the plant, in order to complete S4. The Temporal coverage established for the study included the 2012/2013 crop.

Municipalities of Campos de Julio, Sapezal and Campo Novo do Parecis composed the Geographical Coverage. Technological Coverage took into account technical characteristics, specifications, limitations and assumptions presented for the modeling of Product System. Infrastructure processes were excluded but long-term emission were considered at the analysis.

The allocations of environmental loads that were performed in this study occurred by mass criteria. Table 4 depicts the steps in which the procedure was performed, as well as the values of the allocation factors applied to each of the coproducts.

Table 4. Allocation factor defined by mass criteria

Scenario	Stage	Coproducts	Allocation Factor (%)
S2	Sugar milling	bagasse + sugar juice	97.09
		surplus bagasse	2.91
S2 and S3	Distillation	Ethanol	3.86
		vinasse	96.02
		fusel oil	0.12
S1, S3 and S4	Distillation	Ethanol	9.89
		vinasse	89.74
		fusel oil	0.37
S1, S3 and S4	DDG production	DDG	91.67
		corn oil	0.33

The Life Cycle Impact Assessment (LCIA) was conducted by method ReCiPe – version 1.10 according a problem-oriented approach – midpoint (Goedkoop et al., 2013). The analysis occurred for the impact categories of Climate Chances (CC), Particulate matter formation (PMF), Water depletion (WD) and Fossil Depletion (FD).

In order to maintain the consistency of the analysis, Thermodynamic performance was also established by methods of systemic amplitude: Cumulative Energy Demand (CED) and Cumulative Exergy Demand (CExD). The CED aims to investigate the energy use throughout the life cycle of a good or a service. This method includes both the direct and indirect consumption of energy due to the use (Pimentel et al., 1973; Boustead and Hancock, 1979). Some authors consider CED results as environmental impact performance indicators for energy systems, because the method expresses power flows as of primary energy sources. From this perspective, CED allows to quantifying the intensity of depletion of those reserves (Frischknecht & Jungbluth, 2007).

Due to divergence of concepts and of the lack of clear basis for the characterization of the different primary energy carriers, CED-indicators are organized into two broad categories: non-renewable and renewable resources. Non-renewable resources are allocated in the subcategories of: fossil, nuclear and primary forest. Renewable resources includes the subcategories of biomass, wind, solar, geothermal and water. Common to any of these categories is the thesis that all energy carriers have an intrinsic value, which is determined by the amount of energy withdrawn from nature. However, the intrinsic value of energy resources need not be comparable across the subcategories. CED is calculated per unit process by the expression presented of (Equation 1).

$$\text{CED} = \sum_{i=1}^{n} (K_i \, . \, \text{En}_i) \tag{1}$$

CED = Cumulative Energy Demand per unit process (MJ_{eq})

k_i = amount of material resource i (kg; m^3; MJ)

En_i = intrinsic energy per amount (kg; m^3; MJ) of substance i (MJ_{eq} / (kg; m^3; MJ))

In this study, the method CED – version 1.08 (Frischknecht at al, 2007) was applied to all the subcategories that belong to the categories of Renewable and non-renewable resources.

Classical energy analysis – carried out according the 1st Law of Thermodynamic – consider all the forms of energy as equivalent, without distinguishing among the various types, or ‘qualities’ of energy flows that cross the boundary of a system. However, the usable work potential supplied to the system – exergy – that has been consumed or destroyed due to irreversibility during the process, which is discussed by the 2nd Law of Thermodynamic, is not considered to the analysis (Kotas, 1985).

Combining the 1st and 2nd Laws, the exergy analysis identifies the distribution of the irreversibility of a unit or a system among all the components that make up the process. It is able to identify the most significant contribution to the overall inefficiency of a unit. Therefore, the Exergy analysis provides a Thermodynamic diagnosis from which can be applied engineering actions to improve the overall efficiency of the process (Kotas, 1985).

In this frame, the Cumulative Exergy Demand (CExD) amounts the life cycle exergy demand of product or process (Bösch et al., 2007). Exergy is stored in resources as chemical, thermal, kinetic, potential, nuclear and radiative energy. The assignment of the adequate type of exergy depends on resource use (Szargut, 2005). CExD assess the total exergy requirement of a product by the sum of exergy of all resources used to its obtaining (Equation 2). CExD is calculated by adding up the total exergy requirement of a process over a certain time-period. The exergy requirement of one unit of process output was then obtained by dividing the total exergy requirement by the number of unit outputs during this time-period (Szargut et al., 1988).

$$\mathrm{CExD} = \sum_{j=1}^{m}(m_j \cdot Ex_{(ch)j}) + \sum_{g=1}^{p}(n_g \cdot r_{ex-e(k,p,n,r,t),g}) \quad (2)$$

CExD = Cumulative Exergy Demand per unit process (MJ_{eq})

m_j = mass of material resource i (kg)

$Ex_{(ch),j}$ = exergy per kg of substance i (MJ_{eq} / kg)

n_g = amount of energy from energy carrier g (MJ)

$r_{ex-e(k,p,n,r,t),g}$ = exergy to energy ratio of energy carrier g (MJ_{eq} / MJ)

ch = chemical

k = kinetic

p = potential

n = nuclear

r = radiative

t = thermal exergy

The emergence of life cycle databases enables and facilitates a product-specific approach, since such databases provide the resource demand for each unit process. Hence, improved CExD scores are calculated to indicate the exergy demand of a single product directly (Bösch et al., 2007).

The score – specified in MJ equivalents (MJeq) – is obtained summing up the individual results of the following impact indicators: Non renewable, fossil, Non renewable, nuclear; Renewable, kinetic; Renewable, solar; Renewable, potential; Non renewable, primary; Renewable, biomass; Renewable, water; Non renewable, metals; and Non renewable, minerals. For the purpose of this study the method CExD – version 1.03 (Frischknecht et al., 2007) was applied for all of its resource categories in order to compose the exergy performance indicator.

3.3 Analyses of Results

The analysis of results occurred in two level. The first level verified each approach separately in order to identify benefits, and potential causes for energetic and exergetic losses, and environmental impacts. Deviations like these were taken as opportunities for improvement the technical arrangements. In the second level, a broad discussion combining simultaneously the three dimensions was carried out in order to identify combined effects and synergies.

4. Results and Discussion

4.1 Environmental Performance Analysis

According to the results depicted in Table 5, scenario S1, in that the ethanol production occurs only by using corn, have better environmental performance than the others scenarios in three of the impact categories – CC, WD and FD – defined for the environmental performance evaluation. Moreover, the impact of S1 in terms of PMF was also satisfactory.

Table 5. Environmental performance of the analyzed scenarios: ReCiPe midpoint (M) – v. 1.10

Impact category	Unit	Scenario			
		S1	S2	S3	S4
CC	kg CO_2 eq	811	1039	1022	866
PMF	kg PM_{10} eq	11.2	43.4	40.8	3.69
WD	m^3	16.4	23.3	22.4	16.5
FD	kg oil eq	132	198	191	601

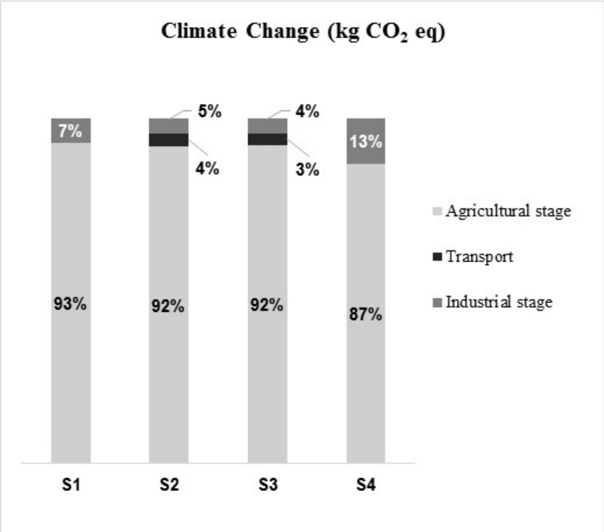

Figure 3a. Contributions for Climate Changes

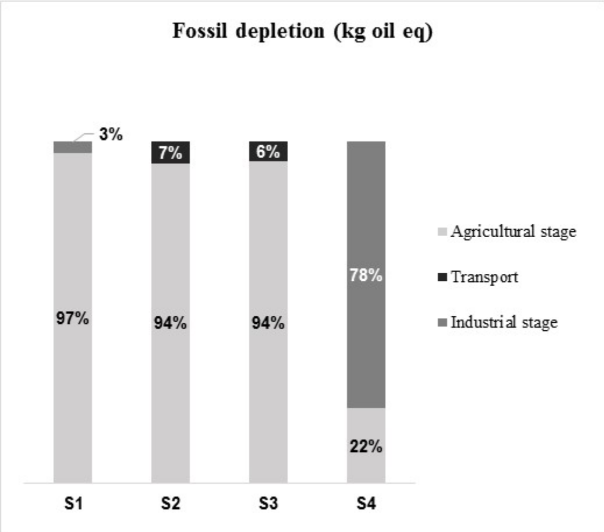

Figure 3b. Contributions for Fossil Depletion

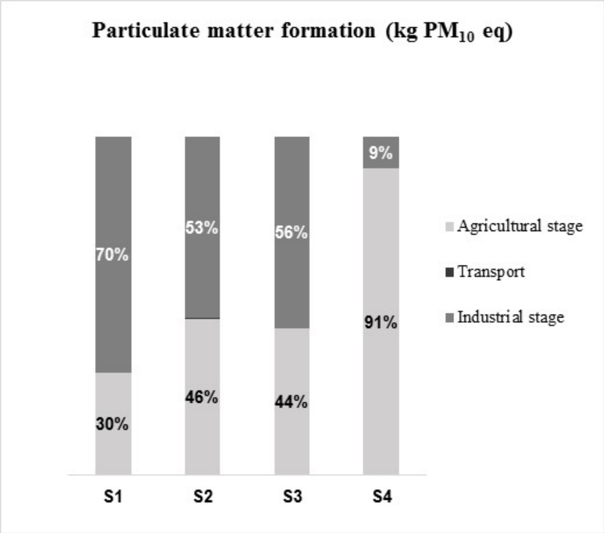

Figure 3c. Contributions for Particulate matter formation

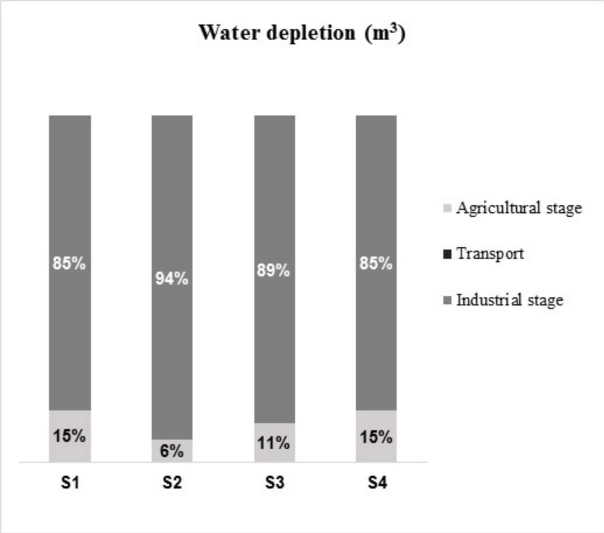

Figure 3d. Contributions for Water Depletion

The contribution of the industrial stage ($58kgCO_2eq/m^3C_2H_6O$) occur due to burning wood chips for power generation and from drying of DDG. FD is also concentrated in the agricultural stage (97%). The positive result can be justified by the use of direct planting system that predisposes minimal interactions with soil and therefore lower consumption of diesel.

The results of S1 as CC and FD were coherent. The main contributions to CC for all scenarios occur in the agricultural stage (Figure 3a). In this frame, the performance of S1 in this category can be justified by two reasons: the expansion of cultivation have occurred on arable land avoiding burning native forest; and, the corn harvest be fully mechanized eliminating the burning of straw, which is including kept intact on the field to protect the soil. The 7% from the industrial stage ($58kgCO_2eq/m^3C_2H_6O$) occur due to burning wood chips for power generation and DDG drying. The performance of S1 in terms of FD is justified in terms of the agricultural stage (97%) from the use of direct planting system that predisposes request minimal soil and therefore lower consumption of diesel.

The impacts of S1 as PMF were also within reasonable limits, considering that the system operates with solid fuel to generate heat. The fact that the wood chips are prepared for such use, in terms of dimensions and especially moisture content (28.6%) was crucial to this result, to raise its LHV and improve the combustion conditions until rectify oxide emissions nitrogen (NO_x), which are also considered for purposes of PMF. S1 showed also a good performance as the WD. Stand out in this category the water consumption at the plant for the preparation and cooking of corn (6.1 $m^3/m^3C_2H_6O$) and in the cooling tower (6.6 $m^3/m^3C_2H_6O$). Although the unit have been built in 2010, there is still potential for implementation of measures to reduce losses and closure of the water circuit.

For scenario S2, in which ethanol production depends only on sugarcane, it were observed the worst performance in terms of CC among all the alternatives under analysis. The advance of cultivation on areas of native Brazilian Savanah (163kgCO_2eq/m^3) and the burning of straw for manual harvesting (253kgCO_2eq/m^3) were decisive to this result, although carbon dioxide (CO_2) and methane (CH_4) emitted in these cases are biogenic. The soil revolving by agricultural machinery for planting releases 154kgCO_2eq/m^3 as dinitrogen oxide (N_2O). Agricultural handling and transport of inputs provided others 464 kgCO_2eq/m^3 of fossil CO_2. The same operations also represent 91% of impact in terms of FD from diesel consumption (Figure 3b). Exactly 90.1% of contributions from S2 to PMF, the worst performance of all the analyzed set for the category, arising from the emission of particulate matter of dimensions $d < 10\mu m$, which are typical of biomass burning. The fact of the bagasse be burned in the boiler under more controlled conditions than those to which it is submitted the straw on the field, apparently does not alter the performance, since 52.4% of the total emission of PMF arises from this operation. The moisture content of this biomass (44.9%) predisposes specific combustion conditions in the boiler, such as adjusting the combustion air and high vacuum between the furnace and the gas discharge duct. This situation provides an increase of drag. Water consumption in S2 was on the same order of magnitude as the others, even though higher by over 42% those obtained by S1 and S4, which were the lowest in the series. Consumptions generated in washing cane (5.4 m^3/m^3), the flue gases emanating from the boiler (2.6 m^3/m^3), and the cooling tower (6.0 m^3/m^3) comprise the major contributions.

The expansion of mechanized harvesting tends to reduce the amount of land being swept away with the cane, decreasing the amount of washing water. The installation of an electrostatic precipitator for removal particulates (ash) in the boiler is another effective measure for rationalization of the water consumption.

The environmental performance of S3 is deeply influenced by the processing of sugarcane ethanol. To meet the requirement of operating the unit during corn processing only with surplus bagasse about 83% of the total volume of ethanol established as the baseline for the study – 56,000 m^3 – should be processed from cane sugar. In these terms, the benefits of not using wood chips for energy production only dampened negative effects provided by the substitution.

One possibility for such participation become more effective is to reduce the moisture content of the bagasse 'that will be burned in the boiler', using the residual energy that is discarded with the combustion gases through the chimney of the equipment. Therefore, the LHV of the bagasse rises, and therefore its potential the energy supply. In this arrangement, the integrated production of ethanol could be better distributed between corn and sugarcane, resulting in overall gains in environmental performance.

The effect in terms of CC of replacing woodchips to natural gas in the production of ethanol from corn (scenario S4) was negative. Although the use of a gaseous fuel with a high energy content (LHV = 38.93MJ/m^3) provides more homogeneous combustion, CH_4 emissions (resulting from fuel processing, and leaks in the transport lines) and CO_2 (via recompression) contribute to 113kgCO_2eq/m^3 to the industrial stage.

A cleaner burning reduces the particulate matter emission to 0.34kgPM_{10}/m^3. Moreover, replacement of boiler fuel improves energy efficiency of the system, which reaches 78%. Therefore, these benefits do not provide reduction of the water consumption as compared to S1. Finally, there was significant increase of impact as FD that is concentrated in the industrial phase (Figure 3d), as could be predictable.

4.2 Energy Performance Analysis: Cumulative Energy Demand (CED)

Table 6 presents results of the evaluation of energy performance of scenarios S1 to S4 obtained from the application of CED method. As can be observer, the best performance in terms of primary energy accumulated over the life cycles in analysis was achieved in the S2 scenario that was followed closely by S3. At the other end, totaling the worst performance appears the S4 scenario.

These results focused mostly on the input of Non-renewable, fossil resources (NRF) and Renewable, biomass (RB). Contributions in terms of Non-renewable, nuclear (NRN) and Renewable, water (RW) were discrete, while for non-renewable, biomass (NRB) and Renewable, wind, solar, geoth. (RWSG) even have occurred.

Table 6. Energy performance of the analyzed scenarios: CED – v. 1.08

Impact category	Unit	Scenario			
		S1	S2	S3	S4
Non-renewable, fossil (NRF)	GJ	5.94	8.75	8.46	27.75
Non-renewable, nuclear (NRN)	GJ	0.05	0.07	0.06	0.05
Non-renewable, biomass (NRB)	GJ	0.00	0.00	0.00	0.00
Renewable, biomass (RB)	GJ	18.72	0.00	0.56	3.28
Renewable, wind, solar, geoth. (RWSG)	GJ	0.00	0.00	0.00	0.00
Renewable, water (RW)	GJ	0.18	0.04	0.06	0.14
Total	GJ	24.90	8.86	9.14	31.22

As in S2 the energy that moves the unit is fully provided for 'bagasse recovered' in the process, the contributions associated with this scenario occur mainly in terms of NRF, particularly due to the diesel consumption of agricultural machinery (8.23GJ) as is indicated in Figure 4a. Although it is registered in the graphic of Figure 4b a contribution from S2 to RB, this was discreet.

S1 showed the best result of all series in terms of NRF. This result is consistent with the performance of the same scenario in terms of FD, for which the adoption of direct planting system reduces diesel consumption of agricultural machinery. Otherwise, the performance of the S1 for RB was far below the other scenarios. The consumptions of wood chips for power generation and drying DDG can explain this result.

As previously reported from the environmental assessment, the processing of sugarcane ethanol has a strong influence on the results of S3. Whereas, in the present situation the overall performance of S2 was superior to S1, the integration between the production of ethanol from corn and sugarcane was positive in terms of primary energy consumption.

NRF's contribution to total primary energy consumption of S4 was 88.9%. Apart from this be an inherent effect of the conditions that guided the development of the scenario, another factor may also explain this result. The amount of intrinsic energy associated with non-Renewable, Fossil corresponds to its LHV. Therefore, this model predisposes that the higher the potential for power generation from fossil fuel, its consumption should be lower for meeting a certain energy demand. Such approach is consistent. In the specific case of S4 the processes of extraction and refining of natural gas, and especially, of transportation over large distances from Bolivian fields cause significant losses, which make this a non-recommended option in terms of energy.

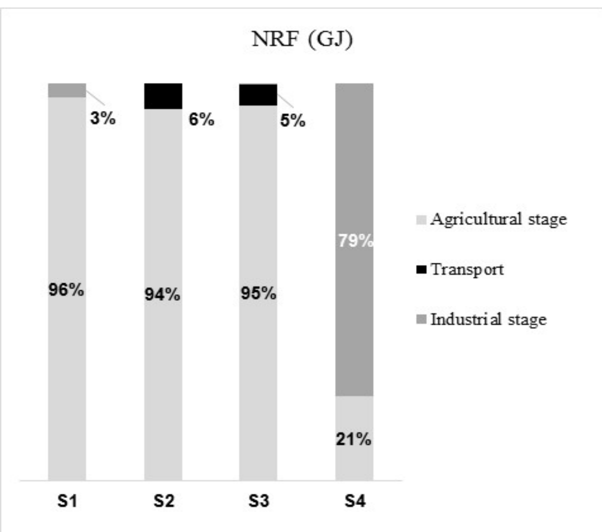

Figure 4a. Contributions for non-Renewable, Fossil

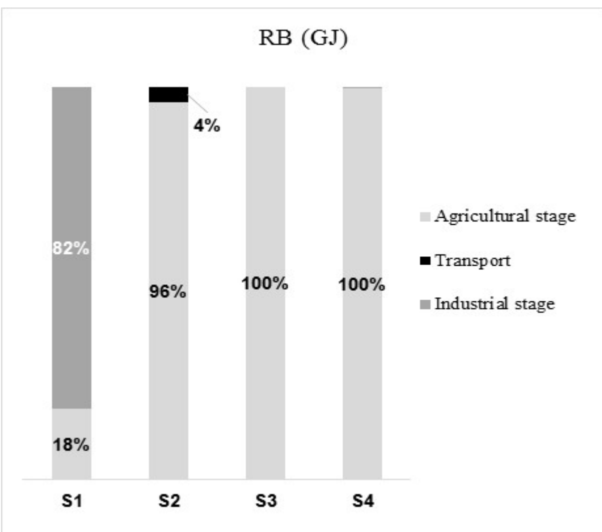

Figure 4b. Contributions for Renewable, Biomass

4.3 Energy Performance Analysis: Cumulative Exergy Demand (CExD)

According to the results in Table 7, the analysis of the exergetic performance has not provided any significant change in terms of impact in relation to the energy profile obtained previously. The ranking previously established from the application of CED method remained unchanged with S2 getting the best performance – followed by S3. Also in this assessment, S4 appeared as the worst alternative.

Table 7. Energy performance of the analyzed scenarios: CExD – v. 1.03

Impact category	Unit	Scenario			
		S1	S2	S3	S4
Non-renewable, fossil (NRF*)	GJ	5.33	8.71	8.32	27.66
Non-renewable, nuclear (NRN*)	GJ	0.05	0.07	0.06	0.05
Renewable, kinetic (RK)	GJ	0.00	0.00	0.00	0.00
Renewable, solar (RS)	GJ	0.00	0.00	0.00	0.00
Renewable potential (RP)	GJ	0.18	0.04	0.06	0.14
Non-renewable, primary (NRP)	GJ	0.00	0.00	0.00	0.00
Renewable, biomass (RB*)	GJ	19.66	0.00	0.59	3.44
Renewable, water (RW*)	GJ	0.19	0.12	0.13	0.18
Non-renewable, metals (NRMT)	GJ	0.00	0.00	0.00	0.00
Non-renewable, minerals (NRMI)	GJ	0.02	0.00	0.01	0.01
Total	GJ	25.43	8.95	9.17	31.48

As had occurred in the energy performance analysis carried out by CED the resource categories of Non-renewable, fossil (NRF*) and Renewable, Biomass (RB*) also provided major contributions regarding the exergetic approach. Moreover, discrete additions were detected in terms of Non-renewable, nuclear (NRN*), Renewable potential (RP), Renewable, water (RW*), and Non-renewable, minerals (NRMI) and the other categories have not provided any inputs.

The prevalence of NRF* and RB* on the other impact categories of CExD resulted in profiles of contribution per stage of the life cycle also very similar to those identified by verification via CED, as can be seen in Figures 5a and 5b. From the discrete analysis per stage, it is noticed that in considering the influence of thermodynamic irreversibility the input of the industrial stage on performance of scenario S4 intensifies from 79%, estimated by CED, to 81%.

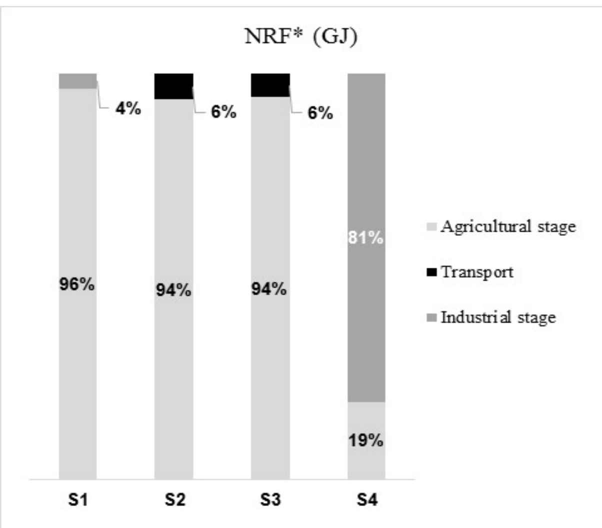

Figure 5a. Contributions for non-Renewable, Fossil

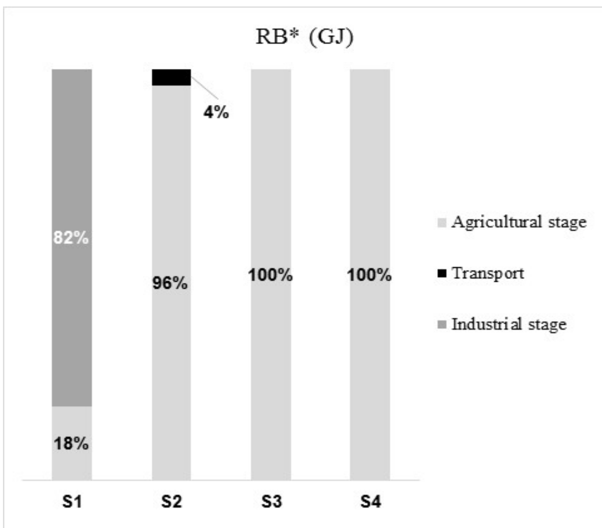

Figure 5b. Contributions for Renewable, Biomass

A comparative analysis of common values revealed a reduction of primary energy consumption in terms of Non-renewable, fossil for all scenarios if CExD performs the estimate. This finding does not corroborate the expectation of the analysis. The consideration of irreversibility of a process from the 2nd Law of Thermodynamics invariably provides higher energy consumption, because are included entropic losses that an analysis of 1st Law disregards. These additions were indeed perceived eg in the categories of Renewable, Biomass and Renewable, Water.

Although the overall indicator provided by CExD has achieved a consistent result - that indicated increase in primary energy consumption in comparison with the accounting performed by CED - the values provided by both methods are close. In addition, there is the incongruity of exergy performance for the category of Non-renewable, fossil. This suggests the occurrence of a few energy losses due to irreversibility despite diverse, and important, energy transformations occur in the various stages of each life cycle.

Therefore, the next step of this research would be the refining of the values Obtained from the exergetic evaluation. This development would be carried out through the application of methods and procedures for estimating exergy for smaller volumes of control, in which only equipments - or at most systems - that comprise each product system would be contained.

4.4 Integrated Analysis

In order to perform a 'combined analysis' of the scenarios under analysis were selected based on criteria of representativeness and precision indicator of environmental performance on Climate Change (CC) method generated by the recipe, and the totalized energy performance indicator provided by the application CED method.

These results were combined as a single geometric mean. No weights were assigned dimensions, in order to avoid distortions and preferences. The results of this mathematical treatment produced an indicator – ID_{global} – whose values are expressed as a generic unit of ‘Points’ (Pt). Table 8 provides the values of ID_{global} for each scenario.

From the composition of the two dimensions, it was observed that the stage S2 is presented as best alternative. Although the GHG emissions due to the production of cane sugar is the most intense of all the options considered, the low primary energy consumption, exactly due to the full utilization of bagasse balance this weakness. S2 is defined by two extreme scenario and, therefore, will not always be comfortable to defend it in terms of addressing the marketing requirements, for the purpose of exporting a product.

Table 8. Combined analysis between Environmental and Thermodynamic dimensions

Scenario	Energy (CED)	CC (kg CO_2 eq)	ID_{Global} (Pt)
S1	24.90	811	142
S2	8.86	1039	96
S3	9.14	1022	97
S4	31.22	866	164

Due to an outstanding influence of ethanol production from sugarcane on the integrated scenario, S3 appears as the second best alternative. At the other extreme are S4 and S1, in which ethanol is produced from corn. Although the use of wood chips and natural gas resulted - each by a different path - in a good environmental performance, the consumption of primary energy contributed to disqualifying these options at least according to this evaluation model.

The use of indicators to determine the environmental and thermodynamic performances of the scenarios under analysis met the expectations that this assessment is proposed. However, a conscious management, aimed at making competitive in the foreign market the ethanol produced in northern Brazil must also consider the social dimension in its scope of application.

The installation of units of ethanol production from sugar cane and corn in the region provides as positive developments: the creation of new jobs, and the establishment of regional economy to support these workers. Furthermore, the maintenance of employability over the entire year for rural workers, due to the manual harvesting of sugarcane is another important social benefit of integrated plants. On the other hand, damage to the health of the farmer under sugarcane cutting, loading of excess weight, and the burning of straw, which also occur during the stage of harvest should be considered by management based on the social variable.

In view of the adherence among the social dimension and the others – environmental and economic – that comprise the Sustainability, it is recommended that a comprehensive analysis of the same issues is conducted.

5. Conclusions

This study carried out a diagnosis of the Environmental and Thermodynamic performances of the production of ethanol from sugarcane and corn in an integrated autonomous distillery. The production of ethanol from corn using wood chips for energy supply of the plant resulted in a homogeneous environmental performance. Factors such as the practice adopted for the corn cultivation – based on direct seeding – and the high LHV of wood energy – in comparison to sugarcane bagasse – support this result.

The analysis of the thermodynamic performance occurred from quantifying the consumption of primary energy. Both in the case in which this measurement was performed assuming ideal transformation processes such as that in which energy losses due to irreversibility was assessed, the production of ethanol from sugarcane had better indexes because the use of bagasse was able to replace satisfactorily any other sources of primary energy. This result remained for a combined analysis between the two dimensions, which related environmental effects in terms of Climate Change with the aggregation of primary energy consumption for ideal systems.

The exergy analysis was effective for the purpose of confirming the results of the Thermodynamic analysis of the 1st Law. However, it is suggested that this quantification to be held back from specific methods and within discrete volumes of control in order to improve the accuracy of its results and thereby accredit it as a consistent approach to such analyzes.

The social issue that permeates the production of ethanol in the north of Mato Grosso directly influences the management process established for the purpose of equating this fuel to its similar in the markets of interest.

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