ETHANOL AND SUGAR PRODUCTION PROCESS FROM SUGAR CANE: RENEWABILITY EVALUATION

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Abstract. *Tropical countries, such as Brazil and Colombia, have the possibility of using their lands for growing biomass to produce biofuels like biodiesel and ethanol. Many studies are available which deal with the use of different sources of biomass for this purpose. From sugarcane, sucrose and other sugars (glucose and fructose) are converted into ethanol through a chain of processes. Considering the combined production of sugar and ethanol, the later is produced using part of sugarcane juice from the milling process and molasses from the sugar factory. These flows are mixed and sent to fermentation and distillation to obtain ethanol. In this work, exergy analysis is applied to the production process of sugar and anhydrous ethanol from sugar cane, using real data of one production plant located in Colombia, with capacity to process 10,000 ton a day of sugarcane. Different stages such as: growing, feedstock transport, processes plant, cogeneration plant and residues treatment are considered. Some environmental indicators based on the exergy concept are proposed for analyzing the sugar and ethanol production. According to these indicators, the Exergetic Density, Rational Exergetic Efficiency and the Renewability Performance Indicator, the ethanol production process can not be considered renewable due mainly to the irreversibilities of the energy conversion processes.*

Keywords*: exergy, ethanol, sugarcane, renewability evaluation*

1. INTRODUCTION

Global warming, urban pollution, reserves depletion and high cost of fossil fuels have been the driving forces for current research on the use of alternative energy sources, especially those derived from biomass. In this sense, ethanol produced from different renewable feedstocks constitutes an alternative fuel for internal combustion engines.

Using ethanol as fuel, decreases fossil fuel consumption and increases energy security. It is considered biodegradable and sulfur free. Its carbon content has a vegetable origin and as a consequence, when it is released during the combustion process, it does not contribute to the increase of carbon dioxide in the atmosphere, reducing global warming and pollution gases. Besides, it can be used neat or blended with gasoline (Mann and Spath, 1997, Wang et al, 1999, Hsieha et al, 2002, Kadam, 2002, Malça and Freire, 2006).

Sugarcane has been used to produce ethanol for almost 90 years. It has proved to be a key raw material due to its high content of sucrose, which through milling, fermentation and distillation, can be used as a feedstock to produce ethanol.

A primary tool to analyze ethanol production process from an integrated point of view is offered by exergy analysis. Exergy is defined as the maximum (theoretical) work that can be extracted from a mass or energy stream when it passes from a given thermodynamic state to one in chemical, mechanical and thermal equilibrium with the environment in a reversible way, interacting only with components the environment. Therefore, any deviation from the environmental reference can be assumed as exergy content (Szargut, Morris et al. 1988).

When exergy analysis is performed, the thermodynamic irreversibility can be quantified as exergy destruction, which is a wasted potential for producing work (Bejan, Tsatsaronis et al. 1996).

Exergy analysis has two key attributes for being used from an environmental standpoint: as the environment is used as a reference state, exergy is a measure of any thermodynamic deviation. Further, it allows comparisons between all inflows and outflows, independently if they are mass or energy streams, using the same physical basis – exergy (Rosen 2002, Ayres 1998).

Exergy analysis has been used to evaluate biodiesel production from cooking oils (Talens et al, 2007). A similar study using palm oil as a raw material was presented by Velasquez, Benjumea and Oliveira Jr (2007). For evaluating the combined production of sugar, ethanol and electricity for different configurations of the cogeneration plant, exergy analysd has been used by Pellegrini and Oliveira (2007), and Pellegrini et al. (2007).

The objective of this work is to apply exergy analysis to evaluate the renewability of sugar and ethanol combined production from sugarcane. The methodology considers the total exergy consumed in nonrenewable feed flows in order to obtain a desired product.

The study takes into account all stages of the sugar and ethanol production, such as: growing and transport of sugarcane, milling, juice clarification, concentration, sugar boiling and refining, fermentation, distillation, dehydration and residues treatment. Also, the utilities plant, responsible for the generation of steam and electromechanical energy used in the process, is analyzed.

Whenever biofuels production is concerned, the chosen control volume includes only the fuel production, but it does not take into account the use of biofuels. For instance, the use of ethanol in internal combustion engines is considered as an independent control volume in the analysis (Malça and Freire, 2006, Kadam, 2002, Botha and Blottnitz, 2006, Carraretto et al, 2004, Sheehan et al, 2004).

Finally, some performance parameters are determined, such as the Mass Performance and Growing Density, Exergetic Density and Rational Exergetic Efficiency. Furthermore, it is proposed an environmental indicator based on the exergy concept, known as "Renewability Performance Indicator".

2. ETANOL PRODUCTION PROCESS

Sugar and ethanol production stages on specific plant production located in Colombia are shown in Fig. 1. Sugarcane planting and growing involve the use of fuels, fertilizers, pesticides and fungicides which are quantified in this work. A total of 120.000 t/ha year of sugarcane are produced, and another 60.000 t/h year of residual biomass as leafs and other lignocellulosic material are left on the land as protecting material. Currently, there are researches being develop to produce ethanol out of those residues via hydrolysis (Cardona and Sanchez, 2006). There are two production routes for sugarcane use: to produce sugar and ethanol as final product, or to produce only ethanol.

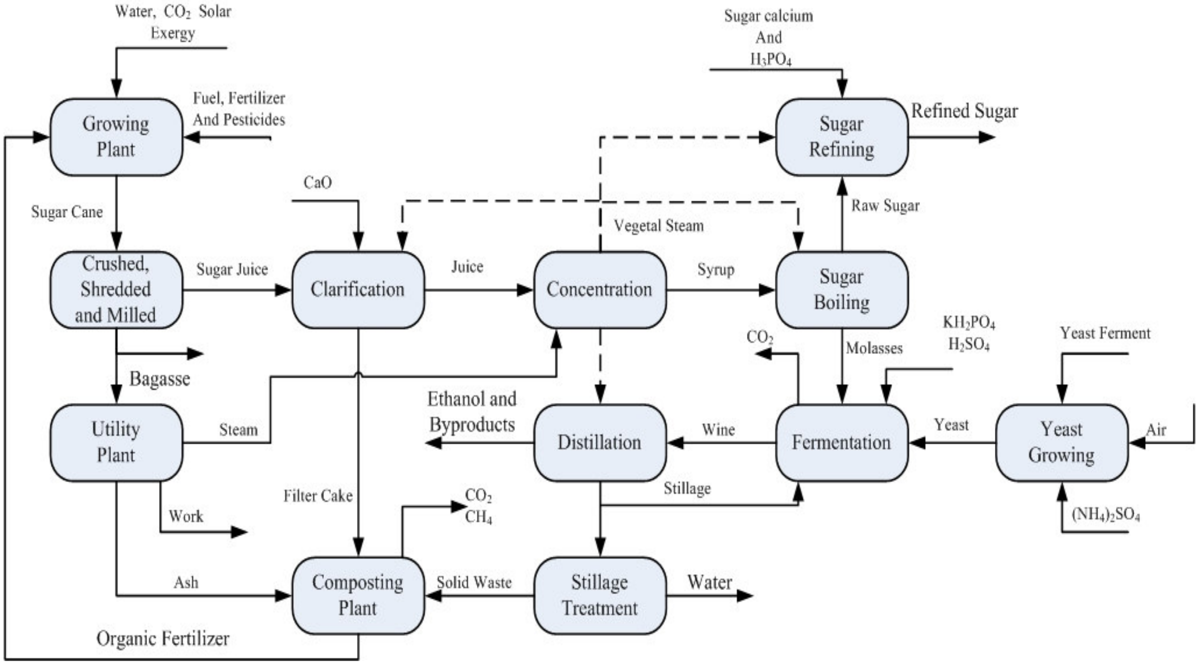

Figure 1. Scheme of sugar and ethanol production process from sugar cane

After the sugar cane cutting, it is transported in special vehicles, consuming diesel oil as fuel, traveling in average 15 km from the land to the production plant. Sugar and ethanol production may be separated into 5 different control volumes:

2.1 Extraction System

Sugarcane is composed mainly by fiber and juice, in which sucrose is dissolved. Thus, the aim of this process is to recover as much juice as possible, but also to produce a final bagasse in suitable condition for fast burning in the boilers. At the industrial level there are two extraction processes: milling and diffusion. Both systems require previous cane preparation, using knives and shredders that operate with direct drive steam turbines.

2.2 Juice Treatment

Raw juice from the extraction system is treated in order to remove nonsugar impurities, using chemicals. During this process, the juice is heated using vegetable steam from the multiple-effect evaporator. CaO is used as precipitator agent for the impurities, and a by-product, known as filter cake, is obtained and used as organic fertilizer.

2.3 Sugar Production

Clarified juice obtained in the treatment plant undergoes a concentration process by removing the water contained in it. The first stage of concentration is carried out in a multiple-effect evaporator. This equipment is responsible for the concentration of juice into syrup, and the production of vegetable steam used for heating purposes in others parts of the process (treatment plant, cooking and distillery). Due to the high viscosity of the syrup leaving the multiple-effect evaporators, it is no longer possible to concentrate it in normal evaporators. Thus, it is used an equipment called pans, which operates under vacuum conditions in a discontinuous way. Evaporation of water creates a mixture of sucrose crystal coated in a sugared solution, which is called the cooked paste. The cooked paste moves to the centrifugation sector and is discharged into the centrifuges. The centrifugal force separates sucrose crystals from the sugar solution. The process is completed by washing the sugar with water and steam while it is still inside the basket. The removed sugar solution returns to the cookers looking for recovery the remaining dissolved sugar, until its exhausted. The sugar solution that lives the pans is called end syrup or molasses, and is sent to fermentation process for making ethanol. Sugar extracted by the centrifuges has high moisture level, being sent to drying before it is packed or refined.

2.4 Ethanol Production

During the fermentation process about 2% of the molasses is used for yeast growing in aerobic conditions, the rest of molasses is used to produce ethanol. When the yeast is submitted to anaerobic conditions, she deviates her metabolic route to produce ethanol and CO_2. The theoretical fermentation reaction yield is 51%, however is only possible to reach about 89 % of this theoretical conversion. Furthermore, during the fermentation process others compounds are produced such as: aldehydes, heavy alcohols, fatty acids, residual biomass, etc. Ethanol at 96 % w/w is produced in the distillation process. Normally two distillation columns are used and some by-products as aldehydes and heavy alcohols are recovered. Stillages (water together with other by-products) are separated, and then about 70% of this liquid mixture is sent again to the fermentation process for increasing the process efficiency. Finally, the stillages are carried to the stillage treatment plant where the water is treated and the solids are separated and sending to the composting plant, where are mixed with ashes and the filter cake to obtain an organic fertilizer. At the end of the process the product is dehydrated using molecular sieves to produce anhydrous ethanol at 99.8% w/w.

2.5 Cogeneration System

Bagasse generated in the extraction system is sent to the cogeneration plant to produce steam to be used in backpressure turbines. This equipment is responsible for the electromechanical demands of the mill. Backpressure steam is used to fulfill the thermal requirements of the process, and its condensate is returned to the boiler. Normally, the electromechanical energy produced is for internal use only.

3. MODELING APPROACH AND SIMULATION

The developed model aims at simulating the steady state operation of sugar and ethanol mills. It is composed of mass, energy and exergy balances, also considering heat and mass transfer conditions, and the correlations for the determination of sucrose-water thermodynamic properties. Thermodynamic properties of sucrose-water solutions were calculated according to the correlations given in Nebra and Fernández-Parra (2005) . Exergy of ethanol-water solutions were taken from Modesto and Nebra, (2005).

The same model has already been used to evaluate different configurations of cogeneration systems in Brazilian sugarcane mills (Pellegrini and Oliveira, 2007, Pellegrini, Burbano and Oliveira, 2007).

The elemental composition in the bagasse, higher and lower heating values (HHV and LHV) necessary to develop the exergy analysis were obtained by experimental analysis developed in the Thermal Laboratory in National University of Colombia, and they were analytically corroborated using expressions proposed in Channiwala and Parikh (2002) and Hugot (1986).

Technical parameters needed for the model were taken from Azúcar Manuelita S.A, a Colombian sugarcane mill with a milling capacity of 3 million tons per year.

This model was implemented and simulated in EES software, using its thermodynamic properties for steam, ethanol and ideal gases such as CO_2, H_2O, O_2, etc (Klein and Alvarado, 2007).

4. PERFORMANCE INDICATORS

For assessing the performance of a plant, several efficiency criteria have been proposed. One of them is the "Mass Performance" (η_m) (Wang et al, 1999), defined by Eq. (1) as:

$$\eta_m = 1000\frac{V_p}{m_b} \quad \text{[L/t sugar cane]} \tag{1}$$

Where, V_p is the ethanol volume produced, and m_b is the sugarcane mass.

Another indicator defined as the "Growing Density (ρ_G)" (Lechón et al, 2005), is shown in Eq. (2):

$$\rho_G = \alpha\frac{V_p}{m_b} \quad \text{[L/ha]} \tag{2}$$

The α factor is the sugarcane produced per land hectare (see Tab. 1).

The "Exergetic Density (ρ_{Ex})" is a new indicator , which is defined using a similar relation to that proposed by The Royal Society (Society, 2008). The proposal is to change the use of energy for exergy in the indicator, as indicated in Eq. (3):

$$\rho_{Ex} = \alpha\frac{\sum_p m_p * b_p^{ch}}{m_b} \quad \text{[kJ/ha]} \tag{3}$$

Where b_p^{ch} is the chemical exergy of biofuel. Another indicator based on the concept of exergy was defined by Kotas (1995), as "Rational Exergy Efficiency", presented in Eq. (4):

$$\psi = 1 - \frac{I}{\sum B_{in}} \tag{4}$$

In order to evaluate the environmental performance in energy conversion processes, many indicators have been proposed. It is agreed that an environmental indicator must have some features: it must be easy to calculate and interpret, allow comparisons between different products and at different times, and be calculated in a scientific form looking for eliminating subjectivities (Gong and Wall, 2001).

Some exergy methodologies have been proposed to evaluate the environmental performance of process production as "Life Cycle Exergy Analysis (LCExA)" (Gong and Wall, 1997), the "Cumulative Exergy Consumption (CExC)" (Szargut, 2005, Szargut et al, 1988), "Exergetic Life Cycle Analysis (ELCA)" (Cornelissen, 1997), "Net Exergy Consumption (CNExC)" (Berthiaume et al, 2001) and "Ecological Cost (ζ_j)" that quantified the exergy cumulative consumption of non renewable resources (Szargut, 2002, Szargut et al, 2002).

Different exergy environmental indicators have been defined such as: "Renewability Indicator (I_r)" proposed by Berthiaume, Bouchard, et al. (2001), "Ecollogical eficiency (η_{eco})" proposed by Toxopeus et al. (2006) "The Environmental Loading Ratio" proposed by Bakshi, (2002), "Sustainability index" (r_B)" (Szargut, 2005) and "sustainability index (SI)" (Rosen et al, In press).

For evaluating any process, but specially those related to the conversion of biomass into biofuels, in this paper the "Renewability Performance Indicator" (λ), defined in Eq. (5), is proposed.

$$\lambda = \frac{\sum_i (B_i)_P}{\sum_j (B_j)_{NR} + \sum_k (B_k)_{DE} + \sum_l (B_l)_W + I} \tag{5}$$

Where: $(B_i)_P$ represents the net exergy associated to the products and byproducts.

$(B_j)_{NR}$, the non-renewable exergy consumed on the chain of production processes; in biofuels production it is considered: growing, transport and plant production.

$(B_k)_{DE}$, the deactivation exergy for treating wastes, when they are carried to equilibrium conditions with the environment. It accounts for the exergy required for passing the streams leaving the system, considered as wastes, up to no harmful environmental conditions (deactivation exergy).

$(B_t)_W$, is the exergy of wastes that are not treated or deactivated.

The term I is the exergy destroyed inside the system, punishing the process for its inefficiencies.

Processes with $0 \le \lambda < 1$ are environmentally unfavorable. For internal and externally reversible processes with nonrenewable inputs, $\lambda = 1$. If $\lambda > 1$, the process is environmentally favourable, additionally, increasing λ implies that the process is more environmentally friendly. When $\lambda \to \infty$, it means that the process is internally and externally reversible with renewable inputs.

Fig 2 shows the control volume used for λ calculations, indicating the processes, the irreversibilities and the terms that cross the frontier: renewable and non renewable resources, deactivation exergy, net products, emissions and residues.

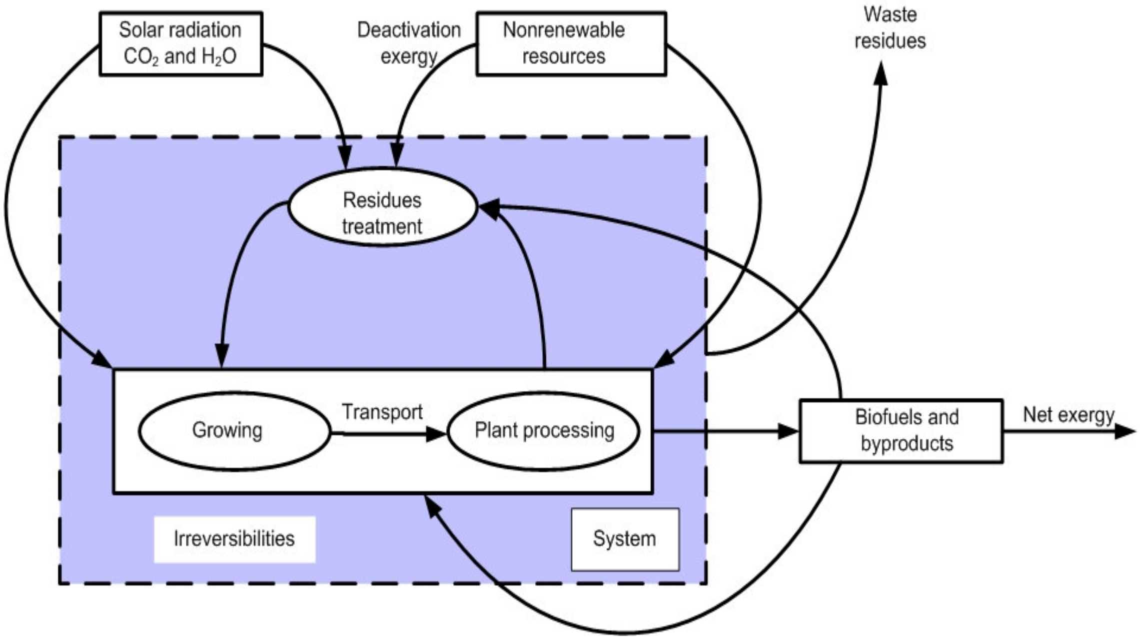

Figure 2. Control volume used for Renewability Performance Indicator

The indicator makes a clear distinction between renewable and nonrenewable resources. The renewable exergy used in the process is not taken into account because it is considered not environmentally harmful (Berthiaume et al, 2001, Cornelissen and Hirs, 2002, Gong and Wall, 1997, Gong and Wall, 2001, Toxopeus et al, 2006).

The deactivation exergy only takes into account the nonreneweable exergy consumed, when the outflows of control volume are treated. Also the non renewable exergy consumed in equipment and plant construction is considered negligible (Malça and Freire, 2006, Shapouri, et al 2002, Kaltschmitt et al, 1997).

In sugar and ethanol production some specific considerations are done: the products obtained are sugar, ethanol and their by products (aldehydes, heavy alcohols, stillage, for instance).

Raw materials as calcium oxide (CaO), Urea ($(NH_2)_2CO$), potassium chloride (KCl), sulfuric acid (H_2SO_4), potassium-dihydrophosphate (KH_2PO_4) and ammonium sulfate $(NH_4)_2SO_4$, diesel oil and gasoline, are considered to be non renewable products, and their exergy values are taken form (Szargut, 2005, Szargut et al, 1988).

The bagasse surplus is mixed with filter cake and boiler ashes to produce an organic fertilizer, decreasing the use of mineral fertilizers. The process is done in a composting plant and fossil fuels, consumed in this processes, are taken into account in the calculations.

The CH_4 produced in the composting plant could be released without any treatment, burned or utilized to generate electricity. All three options have been considered.

The stillage treatment consumes 17.3 kJ/kg stillage, as deactivation exergy to separate the solid material from water (Villegas, 2008). Nevertheless this exergy is not taken into account because it is obtained in utilities plant that uses sugarcane bagasse as fuel.

The residual biomass as leafs and other lignocellulosic material are left on the field as protecting material. Therefore they are not considered as waste or consumers of deactivation exergy.

The contaminated water by fertilizer and pesticides accounts for 1500 m^3, with a concentration of 5 µg/L. If the water is treated by invert osmosis, the exergy consumption will be 2100MJ/ha (Berthiaume et al, 2001). In the analyzed plant production, this water is not treated.

5. RESULTS

The inputs consumed in farming, transporting and processing sugarcane are shown in Tab. 1. Data are taken from statistics of plant production. The Urea ((NH$_2$)$_2$CO) and potassium chloride (KCl) are used as fertilizers. The organic fertilizer produced in composting plant diminished the quantity of mineral fertilizer.

Gasoline is used in airplanes for spread calixim, a commercial product that is used as pesticide. Diesel consumed in the transport of sugarcane to the mill is considered covering 30 km (come and go from the field) in average, it is not taken into account the fuel consumed in farming activities.

Table 1. Inputs for farming, transporting and sugar cane production.

Fertilizers	kg/ha year	Fuel	Value	Biomass production	t/ha year
(NH2)2CO	250	**Gasoline (kg/ha year)**	26,1	**Sugar cane**	120
KCL	300	**Diesel (kg/kg sugar cane)**	9,69x10^{-4}	**Residual biomass**	60
C19H39NO (Calixim)	1.7				

The non renewable inputs consumed in sugar and ethanol production plant are shown in Tab. 2, taken as reference one ton of sugarcane. Other products used in sugar production as calcium saccharine and phosphoric acid are not taken into account due to their low used quantity.

The nonrenewable products quantities used for transformation sugarcane into sugar or ethanol are little compared with one ton of sugarcane that is considered renewable.

Table 2. Inputs in sugar and ethanol production plant per one ton of sugar cane.

Inputs	Sugar and Ethanol		Ethanol	
	m (kg)	**B** (kJ)	**m** (kg)	**B** (kJ)
Calcium oxide (CaO)	0.56	1100	0.56	1100
Sulfuric acid (H_2SO_4)	0.17	284	1.09	1822
Potassium dihydrogenphosphate (KH_2PO_4)	0.38	410	2.41	2555
Ammonium sulfate $(NH_4)_2SO_4$	0.17	854	1.09	5468

The products are shown in Tab. 3, taking into account the same calculation basis. The organic fertilizer is composed of filter cake, ashes generated in boiler and solid material recovered in the stillage treatment plant. CH$_4$ generated in composting plant is considered as a waste product. As the organic fertilizer returns to the land it is not considered as a product: its use only diminishes the amount of fertilizer used in sugarcane growing.

Table 3. Products in sugar and ethanol production plant per one ton of sugar cane.

Products	Sugar and ethanol		Ethanol	
	m (kg)	**B** (kJ)	**M** (kg)	**B** (kJ)
Sugar	122.8	2.156x10^6	-	-
Ethanol	10.89	321539	73.09	2.16x10^6
Heavy alcohols	0.11	3442	0.73	22633
Aldehydes	0.11	2939	0.73	19324
Organic fertilizer	39.3	-	48.3	-

Exergy balances are carried out taking the different production steps as control volumes, in sugar and ethanol production plant. It is considered the chemical and physical exergy content in each flow. The results of the exergy balance, per ton of sugarcane processed, and the rational efficiency are presented in Tab. 4.

The high rational efficiency in separation processes, such as milling, concentration, sugar boiling, refining and distillation, is a consequence of the high value of chemical exergy of the streams when compared to the exergy destroyed (mechanical work and physical exergy in steam).

Processes, in which a chemical reaction takes place, such as fermentation and in the utilities plant, cause an increase in destroyed exergy and their rational efficiency diminishes.

Table 4. Exergy balance in sugar cane plant processing (kJ/t sugar cane).

Process	Inlet	Outlet	B_D	ψ (%)
Milling	6.386×10^6	6.245×10^6	140996	97.8
Clarification	3.455×10^6	3.366×10^6	88758	97.4
Concentration	4.946×10^6	4.845×10^6	100360	98.0
Sugar boiling	3.674×10^6	3.652×10^6	22534	99.4
Refining	2.777×10^6	2.693×10^6	84430	97.0
Fermentation	513833	401847	111985	78.2
Distillation	441338	417298	23420	94.5
Utilities plant	3.077×10^6	887485	2.190×10^6	28.8

The performance indicators proposed from Eq. (1) to Eq. (3) are shown in Tab. 5. They are used to evaluate the performance of sugarcane as a feedstock for ethanol production. The α factor that represents the sugarcane production per ha-year used to calculate ρ_G and ρ_E was taken from Tab. 1. The ethanol volume produced is obtained from mass production data presented in Tab. 3. The sugar and ethanol chemical exergy are 17551.3 kJ/kg and 29515 kJ/kg, respectively (Szargut, Morris et al. 1988).

Table 5. Performance indicator results.

	Sugar and ethanol		**Ethanol**
	Sugar	**Ethanol**	
η_m	122.8 (kg/t)	13.8 (L/t)	92.6 (L/t)
ρ_G (kg/ha)	14740	1307	8771
ρ_E (MJ/ha)	2.973×10^5		2.589×10^5

The "Mass Performance" (η_m) value of 92.6 L/t , obtained when only ethanol is produced, can be compared with the value of 85.4 L/t reported in (Goldemberg et al, 2008) for the Brazilian production and the value between 388 L/t and 403 L/t when corn is used as feedstock (Lechón et al, 2005). The higher values obtained for corn result form the fact that when the mass of sugarcane is considered, it takes into account the amount of fiber and water, differently when corn is concerned.

The "Growing Density" (ρ_G) value of 8771 kg/ha (11112 L/ha) obtained when only ethanol is produced, can be compared with the value of 3061 L/ha when corn is used as feedstock (Kim and Dale, 2005) or the value reported of 6200 L/ha using sugar cane (Society, 2008). In the Brazilian sugarcane production, this indicator takes a value close to 7100 L/ha (Goldemberg et al, 2008). The better result in this indicator is due to two principal factors: the high yield in sugarcane obtained by ha-year (120 t/ ha-year), and fermentation efficiency (91%).

Exergy Density (ρ_E) for ethanol production from sugarcane is 258900 MJ/ha-year. This value can be compared with the one obtained for ethanol production using banana fruit of 85960 MJ/ha-year (Velasquez, Ruiz and Oliveira Jr, 2008) showing that when sugarcane is used as feedstock a better result is obtained. This might be explained by two reasons: banana fruit requires a hydrolysis treatment to convert starch into glucose. Therefore, there is an additional chemical reaction that destroys exergy. Furthermore, the yield in sugarcane is much higher than that of banana fruit (13 t/ ha-year) (Velasquez, Ruiz and Oliveira Jr, 2008).

When sugar and ethanol are produced the Exergetic Density is better than only ethanol is produced. Although the specific exergy of sugar is less than ethanol specific exergy, the mass yield in combining sugar and ethanol production presents better results (see Mass Performance in Tab. 5).

This result shows that exergy destroyed in ethanol production is higher compared to sugar and ethanol production.

The results for different stages of process production to calculate the "Renewability Performance Indicator" (λ) are shown in Tab. 6. The non renewable exergy consumed is divided in two parts: the exergy used in growing sugarcane and the exergy consumed in plant production. Besides are calculated the deactivation exergy, the total exergy destroyed and the exergy of wastes when they are not treated: the gas emissions of boilers and CH_4 emissions in composting plant.

Table 6. Factor obtained for calculating the Renewability Performance Indicator (kJ/t sugar cane).

$(B_i)_P$	2484	$(B_k)_{DE}$	33.75
$(B_j)_{NR}$ (Growing)	76.3	$(B_l)_W$ (Boilers)	252
		$(B_l)_W$ (Composting plant)	1153
$(B_j)_{NR}$ (Plant production)	10.8	I	2758

It can be observed in Tab 6, that there are three quantities that have higher values: exergy in products, emissions and exergy destroyed. These quantities affect the Renewability Performance Indicator results.

The Renewability Performance Indicator (λ) is calculated when sugarcane is used to produce sugar and molasses to produce ethanol. The results are showed in Tab 7.

Table 7. "Renewability Performance Indicator" (λ).

λ_1	λ_2	λ_3
0.56	0.79	0.90

λ_1, is calculating considering the release of CH_4 produced in composting plant. λ_2, considers the free combustion of CH_4, and λ_3, considers its use to power generation, taking an exergy efficiency of 30% in the power generation plant. As the results of the 'Renewability Performance Indicator" (λ) are lower than one, processes using sugarcane as feedstock can be considered nonrenewable. Nevertheless, the indicator presents a better result when the emissions living the control volume are used instead of being destroyed. The destroyed exergy and free emission of CH_4, are the principal factors for the non-renewability of process production; they represent 91.3% of the total value in the denominator of the Renewability Performance Indicator.

6. CONCLUSIONS

The exergy analysis is a tool that can be used to evaluate the behavior in ethanol and sugar-ethanol production processes when sugarcane is used as feedstock.

The rational exergetic efficiency results show that utilities plant and fermentation process are the main sources of irreversibilities.

The "Mass Performance" (η_m) results obtained when sugarcane is used to produce ethanol are smaller than those for corn, due to the fact that sugar cane has other compounds that are not used to produce ethanol as fiber and water.

The "Growing Density" (ρ_G) results show that sugarcane is the best feedstock to produce ethanol, due to its yield in biomass production per hectare-year.

The λ results obtained from sugar and ethanol production show that these processes must be considered as nonrenewable ones, although when emissions are used to generate electricity, this parameter can be improved.

The main cause for the non-renewability of sugar and ethanol production is due to the irreversibilities of the energy conversion processes.

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