EXERGY ANALYSIS OF A SUGARCANE-BASED BIOREFINERY

(Biorefinerías)

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Abstract. Biofuels produced from lignocellulosic biomass as ethanol are renewable alternatives to decreasing the demand for fossil fuels. The purpose of this study is to evaluate the ethanol production using sugarcane as feedstock in a biorefinery through exergy analysis. Thus, the exergy efficiency of the ethanol production processes is obtained and the main variables affecting the process behavior are identified.

Keywords: Exergy, Ethanol, Biorefineries, Sugarcane.

Introduction

Currently, industrial economies are largely dependent on oil industry. However, crude oil reserves are limited and world demand is constantly growing. Meanwhile, there is increasing concern over the impact of these traditional manufacturing processes on the environment. This scenario evidences the importance of reduce our dependence on petroleum feedstock by establishing a bio-based economy and the constant research of alternative energy resources with less environmental impacts, such as biofuels.

In this context, this work based on exergy analysis evaluated the ethanol production from sugarcane. Exergy analysis has been used to evaluate the combined production of sugar, ethanol and electricity taking into account different configurations of the cogeneration plant, have been analyzed using exergy-based costs (Pellegrini and Oliveira, 2011; Velásquez et al. 2012; Pellegrini et al. 2010).

Brazilian sugarcane industry

In Brazil, 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. Developments in bioprocesses are being made to allow the use of amilaceous and lignocellulosic materials to produce ethanol through hydrolysis, fermentation and distillation (Velásquez, 2009).

In 2010, the amount of sugarcane processed in Brazil was 612 million tons, producing 34 million tons of sugar and 26 million m^3 of ethanol. The total area of production corresponds to 7.5 million hectares, near 15% of the total land available for agriculture (Pellegrini and Oliveira, 2011).

For these reasons this raw material plays a significant role in the Brazilian energy matrix and in the future it is seen as a continuous resource use and growth due to their potential as energy.

The Biorefinery Concept

Biorefinery term refers to the conversion of biomass feedstock into value-added chemicals and fuels with minimal waste and emissions. The biorefinery concept is analogous to today's crude oil refinery. Figure 1 shows the comparison between a conventional refinery and a biorefinery.

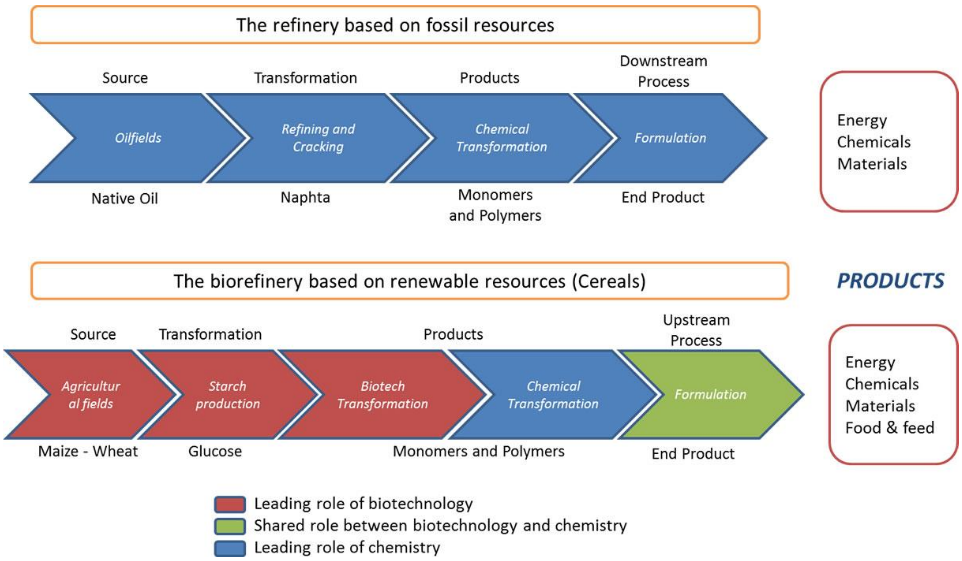

Figure 1. Comparison of refinery versus biorefinery (adapted from Rupp-Dahlem, 2006).

Thermochemical and biochemical conversion products from biomass are upgraded before ultimate refining processes, as shown in Figure 2. Biorefinery includes fractionation for separation of primary refinery products. The main goals of biorefineries are to integrate production of higher value chemicals and commodities, as well as fuels and energy, and to optimize use of resources, maximize profitability, maximize benefits and minimize wastes (Clark and Deswarte, 2008).

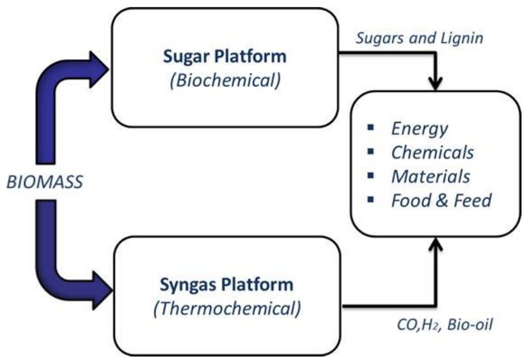

Figure 2. Simplified schematic diagram of a two-platform concept biorefinery (Adapted from Clark and Deswarte, 2008).

Biorefineries are classified based on their system components; platforms, products, feedstocks, and conversion processes as explained in the Table 1.

Table 1. Different types of biorefinery (Adapted from Ghatak, 2011).

TYPE	DESCRIPTION	PRODUCTS / REMARKS
Platforms	Refer to intermediates connecting biorefinery systems and their processes.	C5/C6 sugars, Syngas, Biogas.
Products	Energy products.	Bioethanol and biodiesel or material products like chemicals.
Feedstocks	They can also be sourced from agricultural residues, forestry residues, and industrial wastes (straw, bark, used cooking oils, paper mill black liquor).	Energy crops from agriculture (Corn, Sugarcane, etc.).
Conversion processes	Currently four major groups of conversion processes are involved in biorefinery systems.	Biochemical (*Fermentation*), Thermochemical (*Pyrolysis*), Chemical (*Esterification*), Mechanical (*Size reduction*).

Figure 3 illustrates a sugarcane-based biorefinery with different processing pathways and resulting product mix. It is evident that compared to conventional processing, as illustrated by solid arrows, working in a biorefinery framework can give a lot of operational flexibility, as well as product mix to choose from (Ghatak, 2011).

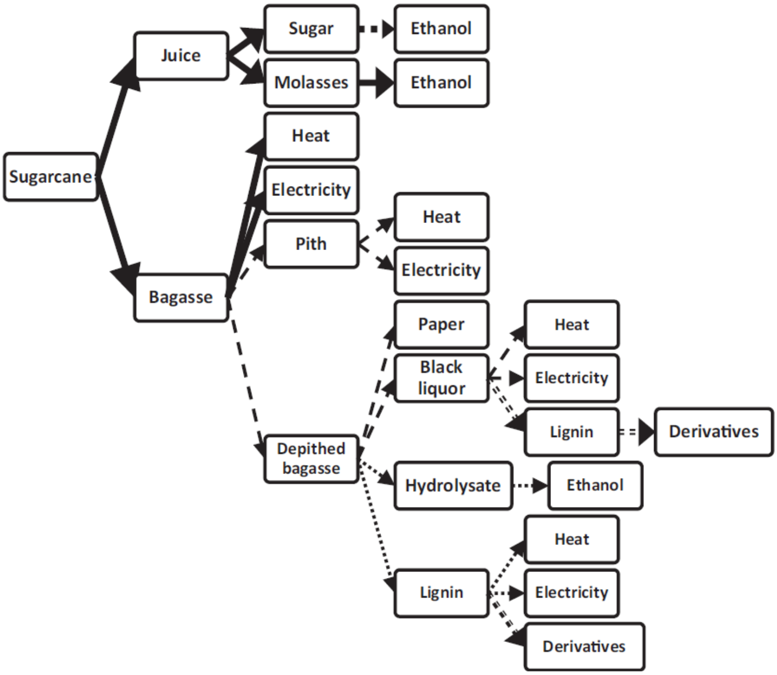

Figure 3. Possible processing pathways for sugarcane (Ghatak, 2011).

The challenge of the next decade will be to develop demonstration plants, which will require cross-sector collaborations and attract the necessary investors required for the construction of full-scale biorefineries. Thus, in the future, the biorefineries technological perspective plays an important role on the energy matrix.

Case study

The case study selected is referenced to an integrated biorefinery and it is focuses on the analysis of the fermentation and the distillation processes, as shown in Figure 4. The chosen settings are used in the sugar and alcohol industry.

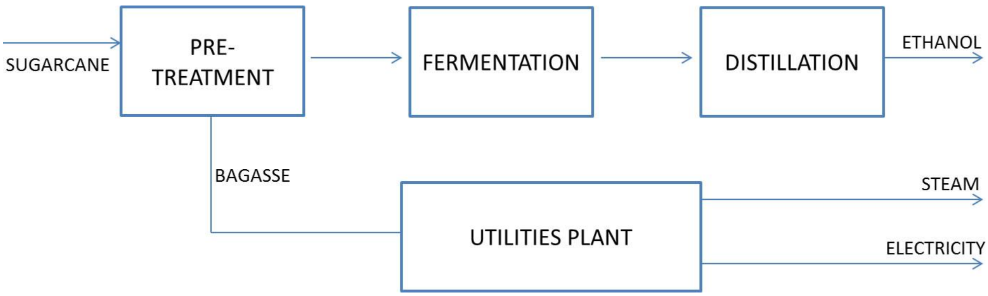

Figure 4. Integrated biorefinery scheme used for the exergy analysis.

This model represents a simplified schematic diagram of a conventional route based on sugarcane, in which the analysis of pretreatment processes was not considered. All simulations were performed using the Engineering Equation Solver software (EES, 2012). The developed models aim at simulating the steady state operation of all control volumes studied. It is composed of mass, energy and exergy balances, also considering heat, work and mass transfer conditions.

The elemental composition of sugarcane bagasse, higher and lower heating values (HHV and LHV), necessary to develop the exergy analysis, were obtained using expressions proposed in literature (Channiwala and Parikh, 2002). Additionally, 50% the moisture content of bagasse (wet basis, %) was considered.

The thermodynamic properties and chemical exergy of other substances as: H_2SO_4, Na_2SO_4, CaO, NaOH, and KH_2PO_4, were obtained form differences bibliographic sources (Szargut, 2005; Kotas, 1995).

Fermentation process

In this process it was considered the mass balance shown in Table 2. This balance includes some of the inputs of modeling fermentation sugarcane mills (Velázquez, 2009b). Additionally, some of the operating variables are treated as ideal, pH 4,0 and T 30 °C were assumed.

Table 2. Exergy balance of the fermentation process.

	VARIABLE	MASS (kg/t-c)	EXERGY (kJ/t-c)
INPUTS	Raw Material (RM)	150,0	2239000
	Water	520,0	23020
	K_2HPO_4	15,0	10701
	H_2SO_4	10,0	16605
	$(NH_4)\ SO_4$	9,1	9901
PRODUCTS	CO_2	60,2	40967
	Wine	645,0	179479

Fermentation process used *Zymomonas mobilis* enzyme, which can absorb the pentose and hexose produced on hydrolysis, converting sugars to ethanol. In addition to ethanol are produced other by-products such as higher alcohols, glycerol, aldehydes and a large amount of carbon dioxide. The fermentation process flow diagram is presented in Figure 5.

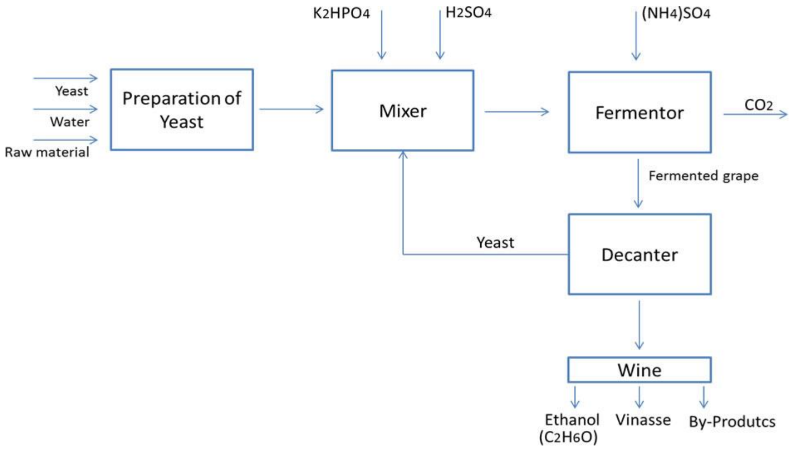

Figure 5. Fermentation process flow diagram.

To calculate the fermentation yield it was used Eq. (1). This parameter is defined as the ratio of the actual amount of alcohol in the amount of sugar fermentation. The theoretical mass of 51.1% corresponds to Gay-Lussac coefficient.

$$Yield_{FERM} = \frac{m_{\text{Ethanol Real}}}{m_{\text{Ethanol Theoretical}}} = \frac{m_{wine}.x_{ethanol}}{0{,}511.m_{sugar}} \qquad (1)$$

However, the exergy efficiency of fermentation is given by Eq. (2). This illustrates a high quality parameter of energy conversion of the fermentation process.

$$\text{Exergy Efficiency}_{FERM} = \frac{B_{WINE}}{\left(B_{RM} + B_{H2O} + B_{(NH4)2SO4} + B_{H2SO4} + B_{w}\right)} \qquad (2)$$

Distillation process

Table 3 shows the mass balance considered in distillation process. This balance takes into account some of the inputs of modeling distillation of sugarcane mills (Velázquez, 2009b).

Table 3. Exergy balance of the distillation process.

	VARIABLE	MASS (kg/t-c)	EXERGY (kJ/t-c)
INPUTS	Wine	528,6	1629580
	Steam	244,6	213953
PRODUCTS	Ethanol (C2H6O)	58,8	1612000
	Vinasse	469,8	20174
	Condensed	244,6	43760

Figure 6 shows the process flow diagram considered in exergy analysis of distillation process.

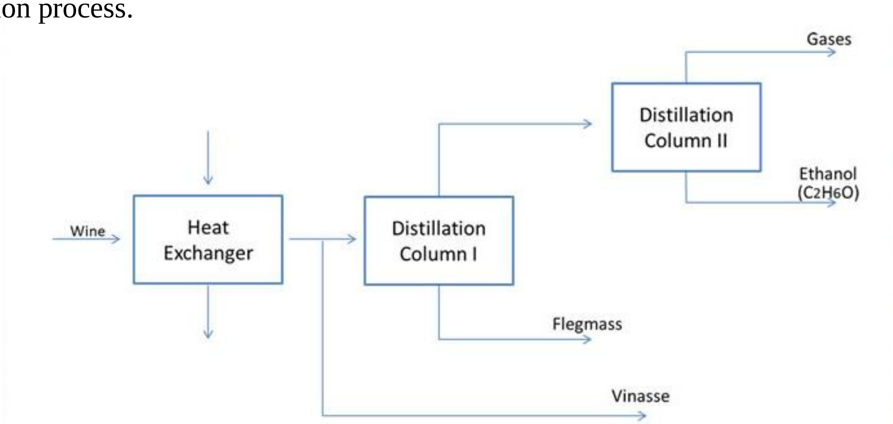

Figure 6. Distillation process flow diagram.

To calculate the distillation exergy efficiency it was used Eq. (3).

$$\text{Exergy Efficiency}_{DIST} = \frac{B_{C2H6O} + B_{VINASSE} - B_{WINE}}{\left(B_{H2O} + B_{STEAM} - B_{CONDESED} + B_{w}\right)} \tag{3}$$

Utilities plant process

This model was designed as a cogeneration plant, taking into account the thermodynamic parameters of utilities plants using bagasse as fuel. Steam was used as a back-pressure turbine at 2.6 bar with isentropic efficiency of 70.0%. (Pellegrini et al. 2007). Additionally, steam was produced in the boiler of low-pressure at 1.8 bar and 200 C. The boiler efficiency and pump efficiency of 70% were considered.

Table 4 shows the inputs and products variables used in this process. The process flow diagram is shown in Figure 7. This model represents a simplified schematic diagram of a conventional utilities plant.

Table 4. Exergy balance of the utilities plant process.

	VARIABLE	MASS (kg/t-c)	EXERGY (kJ/t-c)
INPUTS	Bagasse	167,3	1476000
	Condensed	150	7607
	Steam	150	10701
	Air	1073	1,879
PRODUCTS	Combustion Gases	1396	333909
	Ashes	11,98	8360
	Electricity	-	101586

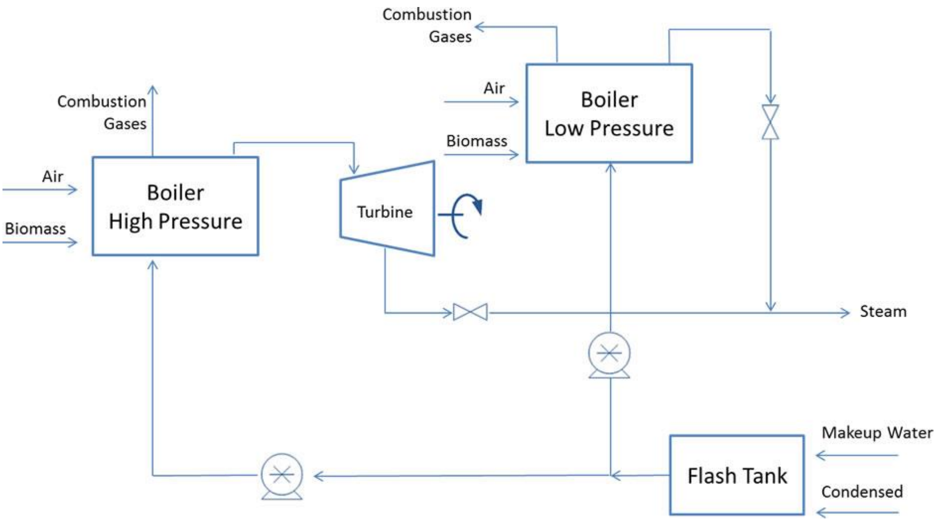

Figure 7. Utilities plant process flow diagram.

The global efficiency of the system was defined as the ratio between the exergy in products (B_P) and the difference between the summation of the exergy in biomass (B_{Bio}) and the exergy in raw materials (B_{RM}), and the flow exergy that it is not used on process (B_W), as shown in Eq. 4.

$$\text{Exergy Efficiency}_{GLOBAL} = \frac{B_P}{\left(B_{BIO} + B_{RM} - B_W\right)} \qquad (4)$$

Results

In order to conduct the exergy analysis of the model considered, the main data parameters from fermentation and distillation processes was estimated, as can be seen from Table 5 and Table 6, respectively.

Table 5. Results obtained from analysis of the fermentation process.

VARIABLE	VALUE
Bw (kJ/t-c)	7000
Heat rejected (kJ/t-c)	-421575
Destroyed exergy (kJ/t-c)	511676
Fermentation efficiency (%)	90
Fermentation exergy efficiency (%)	77

Table 6. Results obtained from analysis of the distillation process.

VARIABLE	VALUE
Bw (kJ/t-c)	7800
Heat rejected (kJ/t-c)	-596195
Destroyed exergy (kJ/t-c)	100310
Distillation efficiency (%)	97
Distillation exergy efficiency (%)	44

On the other hand, the comparison between heat rejected and destroyed exergy in fermentation and distillation processes, is shown in Figure 8.

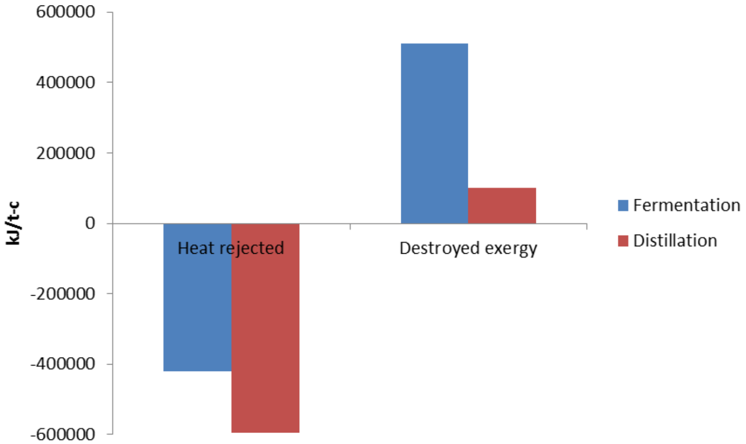

Figure 8. Comparison between heat rejected and destroyed exergy.

Additionally, Figure 9 shows the energy efficiency and exergy efficiency obtained in fermentation and distillation processes.

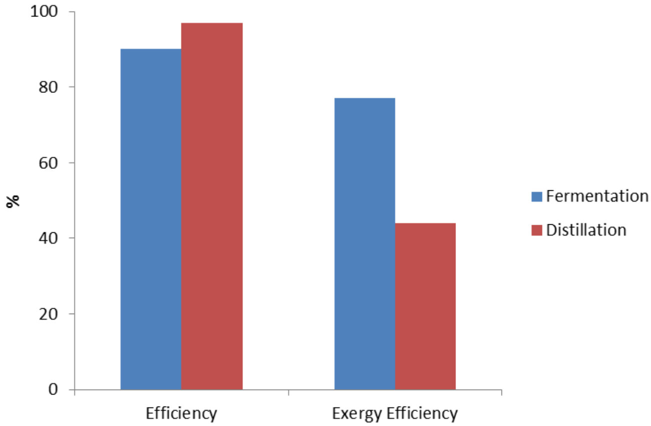

Figure 9. Efficiency and exergy efficiency of the processes analyzed.

The global efficiency of the system was 0.387. As can be seen in Table 7, the most sensitive variable of the utilities plant process measured is the destroyed exergy, which is dependent on the chemical reactions in the combustion process.

Table 7. Results obtained from analysis of the utilities plant process.

VARIABLE	VALUE
Heat rejected h1 (kJ/t-c)	440259
Heat rejected h2 (kJ/t-c)	445381
Destroyed exergy (kJ/t-c)	1187000
Bproducts (kJ/t-c)	1661000
Bresidues (kJ/t-c)	80081
Global efficiency (%)	38.7

Conclusions

The assessment of the fermentation and distillation processes shows a 77% and 44% of the exergy efficiency, respectively. This result is due to entropy generated (exothermic reaction) for the conversion of sugars to ethanol and heat dissipation, which are the main variables affecting the processes exergy efficiency.

Additionally, a better efficiency in these processes can be obtained by considering alternatives as reducing the formation of undesirable byproducts (aldehydes), implementing the extractive fermentation process or increasing the alcohol content of wine to reduce the thermal load in the distillation columns.

The exergy analysis is a tool that can be used to evaluate the behavior in the production chain used to produce biofuels. According to this analysis the global exergy efficiency results for ethanol production from sugarcane, where chemical reactions as hydrolysis, fermentation and combustion are the principal causes of exergy destruction in ethanol production.

Acknowledgements

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