5th International Conference on Contemporary Problems of Thermal Engineering
CPOTE 2018, 18-21 September 2018, Gliwice, Poland
Institute of Thermal Technology

EXERGETIC, ENVIRONMENTAL AND ECONOMIC ASSESSMENT OF SUGARCANE FIRST-GENERATION BIOREFINERIES

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Keywords: Exergy analysis, Thermo-economic, Sugarcane bagasse, Irreversibilities, Cogeneration Systems and Environmental performance.

Abstract
First generation ethanol (1G) contributes to the majority of the ethanol produced worldwide, predominantly based on corn and sugarcane. However, several concerns over the long-term sustainability of this technology, such as its intensive water and land use, potential contamination of soils with the distillation residues, as well as the competition between food and fuel crops are frequently highlighted.
Accordingly, in this work, a detailed process design strategy for biomass to ethanol production (1st-generation ethanol technology) from sugarcane were performed using Aspen Plus® software based on the annexed plant (production of bioethanol and sugar) and autonomous distillery (only bioethanol is produced) systems. Furthermore, a performance comparison in terms of the exergy efficiency and the destroyed exergy rate as quality indicators of the conversion processes are determined to allow identifying potential improvements in the production facilities. Hence, the techno-economic bottlenecks in ethanol production can be overcome by using the exergy efficiency as a process performance index. In addition, the sustainability aspects involved in the process design of the sugarcane biorefineries are discussed through the use of the renewability exergy index. The results showed that the annexed plant has a reduction in the process irreversibilities rate of 6 % approximately, and in the average unitary exergy cost rate of 10 % approximately, in comparison to the autonomous distillery. Even though the proposed methodology is applied to 1G ethanol, it may well be suited for several bioprocesses as a tool to help in taking decisions regarding process design stage for further improvement.

1 Introduction

The first-generation (1G) ethanol is at present produced commercially from edible crops using biochemical methods. Thus, more than the half of the world bioethanol production comes from sugar-containing crops, mainly sugarcane, sugar beets, and sweet sorghum [1]. These crops accumulate high amounts of sugars that can be directly extracted and fermented into ethanol, according to the technology. Sugarcane is so far the most efficient feedstock for bioethanol production, particularly due to low consumption of fossil energy during sugarcane processing [1]. In 2016, US and Brazil were the first and the second largest producers of ethanol in the worldwide, respectively. In the US, approximately 58 billion liters of ethanol were produced, primarily from corn starch using alcoholic fermentation [2]. Otherwise, in the Brazilian scenario sugarcane is one of the most important industries in the national economy, which processes 670.6 million ton of sugarcane to 38.9 million ton of sugar and 28.276,4 thousand m^3 of ethanol [3].
Application of the techno-economic approaches to assess the ethanol production from sugarcane is extensive research field around the world. In this respect, it must be underlined that several Brazilian institutions have been analysed different biorefineries configurations including the ethanol and sugar plants (Ensinas et al.[4], Pellegrini and Oliveira Jr.[5], Pina et al.[6], Albarelli et al.[7], Flórez-Orrego et al.[8]) as well as independent distilleries that focus on exclusively in the ethanol production [9]. Regarding the exergetic assessment of these systems, it should be noted previous results reported in the literature in this field by Ensinas et al.[4]; Pellegrini and Oliveira Jr.[5], Flórez-Orrego et al.[8], Pellegrini et al.[10], Modesto et al.[11], Palacios-Bereche et al.[12] and Pina et al.[13].
Furthermore, an extension of this approach that covers the integration of the first- and second-generation ethanol through the use of lignocellulosic materials in the supply/product chain has been realized looking to improve the ethanol production rate (Ensinas et al.[14]; Dias et al.[15]; Bonomi et al.[16]).
This work deals with the biochemical method of ethanol production from sugarcane in a Brazilian biorefinery context. Hence, a general model to the autonomous distillery (1G-AUT) and to the ethanol and sugar production processes (1G-ANX) were developed based on data for typical plants, and an economic, environmental and exergy analysis for both systems were performed.

2 Process description

Data for the autonomous distillery and the annexed plant processing 4 million tonnes of sugarcane (TC) per season recovering 50 % of sugarcane straw with 30 wt.% moisture are considered.
The processes for the sugarcane distillery and the annexed plant were separated into several control volumes. ***Extraction System:*** In this process it is obtained the bagasse, which represents a by-product in suitable condition for burning in the boilers. Two kinds of devices are employed to perform this operation: mills and diffusers. A comparison of milling and diffusion systems from sugarcane is presented in Palacios-Bereche et al.[17]. ***Juice Treatment:*** In this step, the raw juice from the extraction system is treated to remove non-sugar impurities, using chemicals *(Sulfuric acid-H_2SO_4, Ammonium hydroxide-NH_4OH (nutrients), Phosphoric acid-H_3PO_4, Calcium Oxide-CaO*). During this process, the juice is heated using vegetable steam from the multiple-effect evaporator. ***Sugar Production:*** In this stage, boiling, crystallization, and drying processes are carried out. The sugar solution is denominated 'molasses' or 'syrup' and is used to produce ethanol by fermentation. Sugar extracted by the centrifuges has high moisture level, being sent to drying before it is packed. ***Ethanol Production:*** This block included the alcoholic fermentation, distillation, rectification and dehydration steps. The Melle-Boinot fermentation process is most commonly used in the distilleries in Brazil. The alcohol in the broth is recovered by distillation, which uses the different boiling points of the various volatile substances present to separate them [5].
Since ethanol and water form an azeotrope with concentration around 95 wt%, conventional distillation

is used to produce hydrated ethanol, but alternative separation processes must be used to produce anhydrous ethanol, including azeotropic and extractive distillation and molecular sieves [15].
Combined Heat and Power-CHP: This system is responsible for the electromechanical demands of the mill. Hence, the bagasse generated in the extraction step is sent to the utility plant to raise steam to be used in extraction-condensing turbine.
The main parameter conditions of the process that are representative for typical factories in Brazil are indicated in Table 1 [18]. Figure 1 displays a diagram of the ethanol–sugar–electricity production considered in these analyses.

Table 1: Main parameters used in the simulation models.

Parameters	***Value***
Crushing capacity	4 million TC/year
Harvest period	200 days
Effective hours operation (h/season)	5280
Sugar extraction	
Efficiency of sugar extraction in the mills	96 %
Bagasse moisture	50 %
Juice treatment and concentration	
Temperature (first juice heating)	70 °C
Phosphate content of the juice after H_3PO_4 addition	250 ppm
Amount of lime (ethanol/sugar production)	0.6/1.0 kg CaO TC^{-1}
Syrup	65° Brix
Ethanol production	
Fermentation	
Fermentation Temperature	33 °C
Conversion of sugars to ethanol	89.5 %
Ethanol content in the wine	80 g L^{-1}
H_2SO_4 addition in yeast treatment (on 100 % basis)	5 kg $m^{-3}_{ethanol}$
Distillation	
Vinasse and phlegmasse ethanol content	<200 ppm
Hydrated ethanol purity	93 wt%
Feed temperature	150 °C
Steam pressure	6 bar
Ethanol recovered as final product	81.4 %
Anhydrous ethanol purity	99.6 wt%
Sugar production (*Crystallization and Drying)*	
Sugar Brix	99
Sugar Purity	99.6 %
Sugar overall recovery	76.5 %
Moisture content of the dry sugar	0.1 %
Outlet temperature of the sugar	35 °C
Cogeneration system	
Pressure of the boiler system	65 bar
Steam temperature	485 °C
Boiler efficiency (LHV basis)	87.7 %
Turbine isentropic efficiency	85 %
Generator efficiency	98 %
Energy demand of the process	30 kWh TC^{-1}

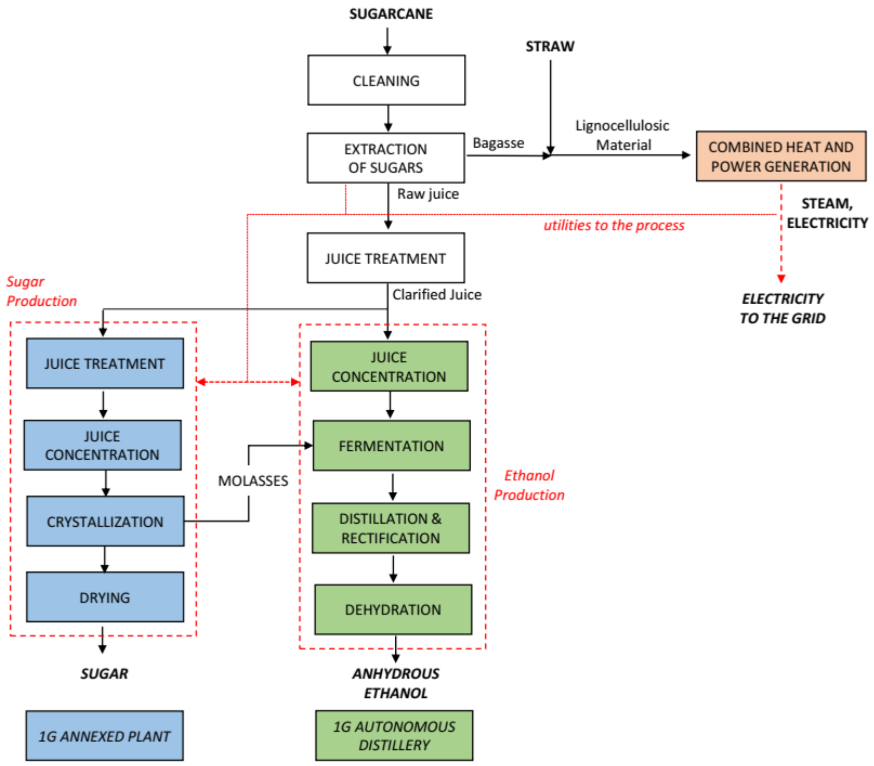

Figure 1: Process flow diagram of the first generation ethanol process and electricity production.

3 Methodology

Mathematical models are used to simulate the steady-state operation of plants producing ethanol, sugar, and electricity (annexed plant, 1G-ANX) and producing ethanol and electricity (autonomous distillery, 1G-AUT). Figure 2 shows a diagram of the design methodology for the assessment of the biorefineries configurations.

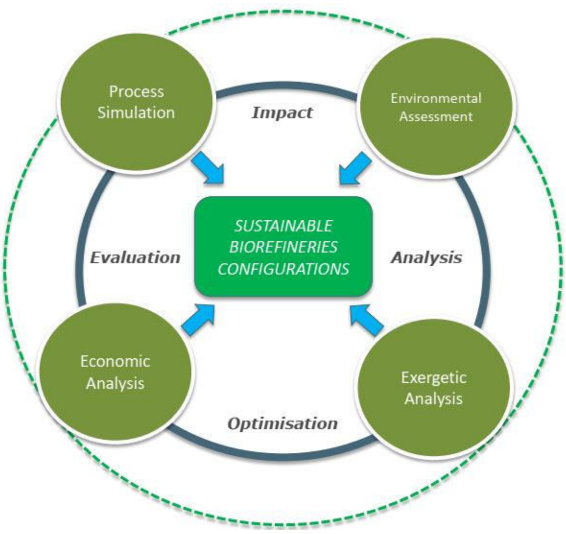

Figure 2: Assessment methodology for the sustainable biorefineries configurations.

3.1 Modelling Approach

The sugarcane biorefineries were simulated to determine mass, energy, and exergy balances. Thus, the Eq.(1), Eq.(2) and Eq.(3) illustrated the expressions used to obtained these balances for a generic control volume (CV), respectively.

$$\sum_{inlet} \dot{m}_i = \sum_{outlet} \dot{m}_e \tag{1}$$

$$\sum_{inlet} \dot{m}_i h_i + \dot{Q}_{CV} = \sum_{outlet} \dot{m}_e h_e + \dot{W}_{CV} \tag{2}$$

$$\sum_{inlet} \dot{m}_i b_i + \dot{Q}_{CV}\left(1 - \frac{To}{T}\right) = \sum_{outlet} \dot{m}_e b_e + \dot{W}_{CV} + \dot{I} \tag{3}$$

where $\sum_{inlet} \dot{m}_i b_i$ represent the exergy of the process inputs ($\dot{B}_{inputs}$), $\sum_{outlet} \dot{m}_e b_e$ the exergy of the process output ($\dot{B}_{products}$), and ($\dot{I}$) the Irreversibilities (exergy losses).

3.2 Process Simulation

The process simulation are carried out by the using of Aspen Plus® V8.6 software. Since processes streams in ethanol plants are complex multi-component/phase, the thermodynamic method used in the simulation was the non-random two-liquid (NRTL) model for the calculation of activity coefficients in the liquid phase, while ideal behavior was assumed in the vapor phase modelling in order to determine the thermo-physical properties of each flow present in the system.
Alternatively, the NRTL-HOC (Hayden-O'Connell) method was used for vapor-phase calculation when the concentration of acetic acid and other carboxylic acids is significant, like on the fermentation and distillation steps, as recommended by Bonomi et al. [18]. In the cogeneration plant, an enhanced SRK equation of state (EOS) based on the semi-empirical Redlich-Kwong with Soave modifications was used, since it is adequate for high temperature gases. In addition, STEAMNBS method was used for the steam streams, once it accurately represents pure water and steam for a wide range of pressures and temperatures [19].

3.3 Exergy calculation

The exergy method, which combines the First and Second Law of Thermodynamics, was applied to assess the performance of the various components in the annexed plant and autonomous distillery. Exergy is defined as the maximum work that can be obtained by means of reversible processes from a thermodynamic system that interacts with the components of the environment until the dead state equilibrium is attained [20]. The thermodynamic properties of the streams and substances present in the processes are evaluated at ambient conditions (298.15 K and 1 atm), T_0 and P_0, respectively. In addition, the thermodynamic value of energy and materials that is based on a potential work exchange is measured with reference to the exergy reference environment that is a conceptual natural environment. The exergy reference environment is composed of common substances, selected for each chemical element [1]. The exergy analysis throughout this work was conducted using the data of mass flow rate, temperature, pressure, enthalpy, entropy and composition of each stream obtained in Aspen Plus®. For convenience, the sum of physical and chemical exergy called thermal exergy (B_{th}) as indicated by Szargut [20] was used for the total specific exergy calculation. Thus, the kinetic and potential exergy are assumed to be neglected. The physical (B_{ph}) and chemical (B_{ch}) exergy were determinate according to Eq.(4) and Eq.(5).

$$B_{ph} = H + H_0 - T_0(S + S_0) \tag{4}$$

H Enthalpy flow rate (kW),
T_o Temperature at the reference state,
S Entropy rate/flow rate (kW/K).

$$B_{ch} = \mathrm{n}_{mix}\left[\sum_i x_i b_i^{ch} + R_u T_0 \sum_i x_i ln \Upsilon_i x_i\right] \tag{5}$$

Where n_{mix} is the total amount of moles of all constituents in a mixture, x_i is the mole fraction of component i in the mixture, and b_i^{ch} is the standard chemical exergy. The b_i^{ch} of the compounds was estimated using Szargut [20], as indicated for lignocellulosic biomass in Silva Ortiz and Oliveira Jr., [21] and [22]. In addition, the b_i^{ch} for compounds not available in the specialized literature of the exergy field was calculated according to the technical fuels procedure based on net heating values and atomic ratios [20].

3.4 Performance indexes

Since exergy can be considered as a quality measure of the products, by-products, and residues at environmental/system conditions, it serves not only for defining indicators to assess the performance of chemical processes, but also as an indicator of environmental impact. Several technical indexes were proposed to evaluate the performance of the sugarcane biorefineries based on thermodynamic indicators. ***Energy efficiency:*** Is defined by the ratio between the useful output (*products=ethanol+sugar+suplus electricity*) and input (*resources=sugarcane and straw*) of an energy conversion process, Eq.(6).

$$\eta_E = \frac{\sum(\dot{m}\,.LHV)_{products} + \dot{w}_{net}}{\sum(\dot{m}\,.LHV)_{resources}} \tag{6}$$

Exergy efficiency: Is the ratio between the exergy of the products and the exergy of the resources, as indicated in Eq.(7).

$$\eta_B = \frac{\sum \dot{\mathrm{B}}_{products}}{\sum \dot{\mathrm{B}}_{resources}} \tag{7}$$

Renewability exergy index (λ): This indicator takes into consideration the exergy associated to the useful products ($\mathrm{B}_{\text{products/by-products}}$) of a given energy conversion process, the destroyed exergy or total process irreversibilities ($\mathrm{B}_{\text{destroyed}}$), the exergy associated to the fossil fuels ($\mathrm{B}_{\text{fossil}}$) required, the needed exergy to disposal the wastes, and the exergy related with emissions, residues and not treated wastes [23]. Depending on the λ value obtained from Eq.(8), it indicates that: *(i).* Processes with $0 \leq \lambda < 1$ are environmentally unfavorable, *(ii).* For internal and externally reversible processes with non-renewable inputs, $\lambda = 1$, *(iii).* If $\lambda > 1$, the process is environmentally favorable, and additionally, increasing λ implies that the process is more environmentally friendly, *(iv).* When $\lambda \rightarrow \infty$, it means that the process is reversible with renewable inputs and no wastes are generated.

$$\lambda = \frac{\Sigma \dot{B}_{\text{products}}}{\dot{B}_{\text{fossil}} + \dot{B}_{\text{destroyed}} + \dot{B}_{\text{deactivation}} + \dot{B}_{\text{disposal}} + \Sigma \dot{B}_{\text{emissions}}} \tag{8}$$

$\dot{B}_{products}$	Exergy associated to the useful products and by-products,
$\dot{B}_{fossil}$	Exergy related to the fossil fuels required,
$\dot{B}_{destroyed}$	Destroyed exergy or total process irreversibilities,
$\dot{B}_{deactivation}$	Exergy associated with the deactivation and treating wastes, when they are carried to equilibrium conditions with the environment,
$\dot{B}_{disposal}$	Exergy rate related to waste disposal of the process,
$\dot{B}_{emissions}$	Exergy rate of wastes that are not treated or deactivated.

CO_2 equivalent rate ($BCO_{2\,EE}$): This indicator represents the relation between the estimate global CO_2 equivalent emissions emitted into the atmosphere due to the operation of the plant and the exergy of the products ($B_{products}$) for each configuration, as shown in Eq.(9).

$$BCO_{2\,EE} = \frac{\text{Global CO}_{2\,equivalent\ emissions}}{\text{B}_{\text{products}}} \tag{9}$$

3.5 Economic Analysis

For the techno-economic assessment, the capital investment (CAPEX) was estimate for each biorefinery configuration. The equipment sizing was defined based on the simulations results, and the economics were estimated for each scenario following well-known methodologies [24, 25, 26]. The purchase cost of most equipment was estimated from equipment cost databases, and adjusted using correlations from literature Turton [24] and Ulrich & Vasudevan [25] to detail the specific process pressures and material. The cost of decanters and distillation columns were estimated using built-in cost models in Aspen. The purchase cost was corrected to 2017 using the Marshall and Swift Index, and the installation cost was estimated using suitable factors from the literature [24, 25, 26].

4 Results

The findings of this study indicate the relationship between the exergy and the sustainability aspects involved in the process design of the 1G-AUT and1G-ANX ethanol plants. Table 2 reports the data sources used in each biorefinery configuration to determine the renewability exergy index (λ). It was found that the annexed plant scores better considering the performance indexes previously defined (*Section 3*) with respect to the autonomous distillery.

Table 2: Renewability index (λ) for the annexed plant and the autonomous distillery systems.

	1G-ANX	*1G-AUT*
B chemical inputs (Fossil) ***[kW]***	*6720*	*3309*
Sulfuric acid (H_2SO_4)	975	1547
Ammonium hydroxide (NH_4OH)	907	1442
Phosphoric acid (H_3PO_4)	42	41
Calcium oxide (CaO)	4800	279
B products ***[kW]***	*627.524*	574.669
B surplus electricity	154.865	154.627
B ethanol	264.756	420.042
B sugar	207.903	0
B by-products and residues ***[kW]***	*47.121*	*71.285*
Filter cake	11.755	23.324
Vinasse	35.366	47.961
B emissions ***[kW]***	*35.530*	*35.574*
B destroyed or Irreversibilities (I) ***[kW]***	*888.629*	*941.485*
Renewability exergy indicator (λ)		
Considering only products	0.67	0.58
Considering products and by-products	0.72	0.65

It is important to note that the exergy values of the net CO_2 emissions are similar for both plants. Regarding the categories shown for the λ index, the results indicated that the biorefineries processes (1G-ANX and 1G-AUT) were categorized as environmentally unfavorable, which means that the exergy of the products could not be used to re-establish the environment to the conditions prior to the occurrence of the process. In addition, when it is considered the exergy values of products and by-products of these configurations, the renewability of the production processes could not be assured even for an alternative low-carbon fuel as sugarcane ethanol.

4.1 Exergetic analysis of a sugarcane-based biorefineries

Regarding the exergetic assessment of the 1G-AUT and 1G-ANX systems, an exergy analysis comparison based on technical data for typical first-generation plants is shown in Table 3. The traditional 1G Mill corresponds to an annex plant producing sugar and ethanol (with 50% of sugarcane used for sugar, 50% for ethanol). It was also included several configurations at the CHP unit (*Back-pressure, Condensing/Extraction steam turbines-ST*) for the steam generation at different levels. In addition, the relation between the exergy destroyed or Irreversibilities ($\dot{I}$) and the exergy of the products (B_P) for these configurations were determinate. It is emphasized that the irreversibilities rate and the exergy efficiency were obtained applying the exergy balance expression introduced in Eq.(3) and the efficiency performance index $\boldsymbol{\eta_B}$ shown in Eq.(7), when these criteria were not reported by the authors. In those cases, the specific exergy values of the inputs considered were: Sugarcane 5130 kJ/kg, Straw 16725 kJ/kg, and Bagasse 9667 kJ/kg. Concerning the exergy of the products, it was adopted for sugar 17479 kJ/kg and for ethanol 27042 kJ/kg.

Table 3: Exergetic assessment of the 1G ethanol plants.

Description	***Configuration***	***Superheated steam [bar, °C]***	***η_B [%]***	***Bdest. [MW]***	***Ratio [I/Bp]***
[a] Rankine without straw *(Condensing ST)*	*1G-AUT*	80 / 500	44.59	389	1.24
[b] Base case *(Back-pressure ST)*	*1G-ANX*	22 / 300	36.10	470	1.77
[c] Case I *(Conf. I - Back-pressure ST)*	*1G-AUT*	100 / 530	35.65	378	1.32
[c] Case II *(Conf. I - Back-pressure ST)*	*1G-ANX*	100 / 530	40.11	386	1.20
[c] Case I-TI *(Back-pressure ST, thermally integrated)*	*1G-AUT*	100 / 530	33.85	296	1.09
[c] Case II-TI *(Back-pressure ST, thermally integrated)*	*1G-ANX*	100 / 530	38.10	273	0.89
[d] Base case - Ethanol distillery *(Hydrated ethanol without surplus electricity)*	*1G-AUT*	21 / 300	32.15	298	1.31
[d] Configuration A *(Hydrated ethanol and surplus electricity)*	*1G-AUT*	67 / 515	34.27	310	1.27
[d] Configuration B (*Electrification of the milling)*	*1G-AUT*	67 / 515	34.72	312	1.27
[d] Configuration C (*Harvest, condensing ST)*	*1G-AUT*	67 / 515	36.45	394	1.52
[d] Configuration D (*Harvest, electrification of the milling and condensing ST)*	*1G-AUT*	67 / 515	36.77	389	1.49
[d] Configuration E (*Harvest, Multiple effect distillation)*	*1G-AUT*	67 / 515	37.54	417	1.57
[e] Base case - Traditional Mill	*1G-ANX*	21 / 300	43.50	323	1.34
[e] BPST - Back-pressure ST	*1G-ANX*	67 / 515	45.60	316	1.22
[e] CEST - Condensing-Extraction ST	*1G-ANX*	67 / 515	44.40	354	1.32
[e] SuSC - Supercritical Steam Cycles	*1G-ANX*	292 / 590	50.00	322	1.06
[f] Base case - Autonomous distillery	*1G-AUT*	65 / 480	37.58	440	1.66
[f] Joint production conventional process	*1G-ANX*	65 / 480	44.30	393	1.26
[g] Base case - Autonomous distillery	*1G-AUT*	67 / 480	28.4	424	1.41
In this study - Annexed plant	*1G-ANX*	65 / 485	41.39	888	1.42
In this study - Autonomous distillery	*1G-AUT*	65 / 485	37.90	941	1.64

[a]Modesto et al. [11], [b]Ensinas et al. [4], [c]Pina et al. [13], [d]Pellegrini et al. [10], [e]Pellegrini and Oliveira [5], [f]Albarelli et al. [7] and [g]Palacios-Bereche [12].

4.2 Exergy destruction and exergy-based efficiencies

Figure 3 indicates the exergy efficiency of the different sub-systems of the 1G-AUT configuration. In addition, Figure 4 exhibits the exergy destruction rate of this process. In terms of the irreversibilities per litter of ethanol produced [kWh/l], it was obtained: Cleaning, preparation and extraction (milling unit) 1.634, Juice treatment (clarification unit) 0.506, Juice concentration (evaporation unit) 0.114, Fermentation 2.158, Distillation 0.566, Dehydration 0.075, Condensate Tank 0.054 and Cogeneration system 8.00.

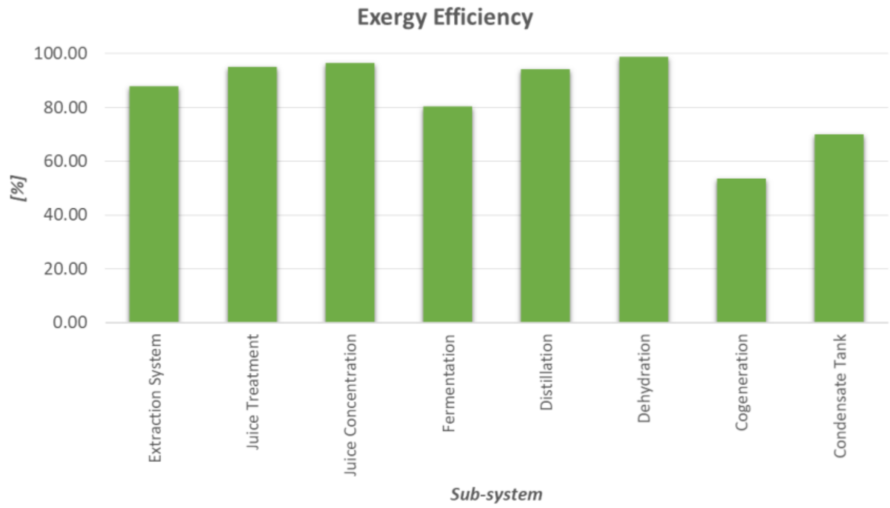

Figure 3: Exergy efficiency of the components of 1G-AUT configuration.

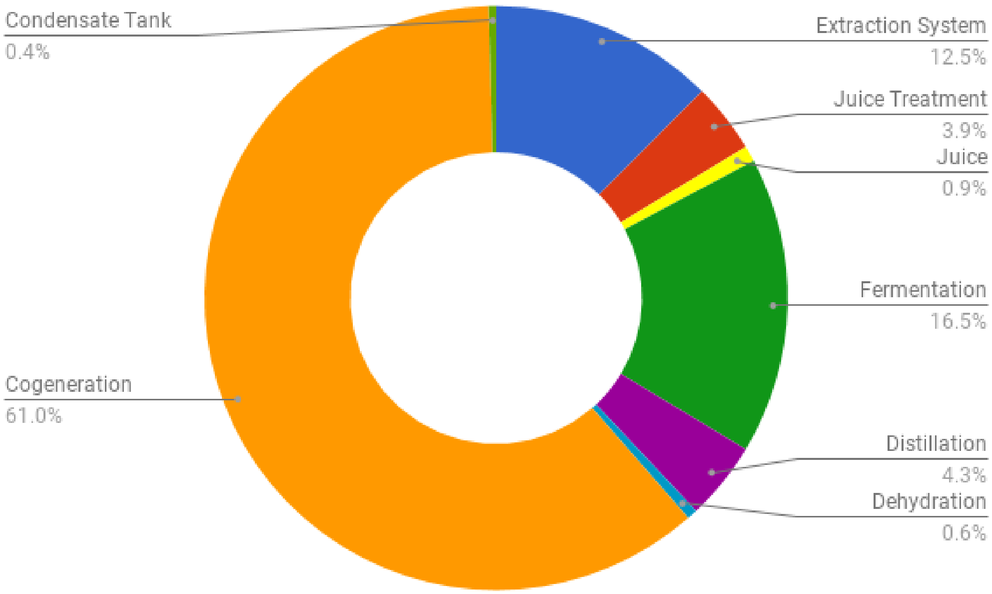

Figure 4: Percentage destroyed exergy of the 1G-AUT system.

On the other hand, Figure 5 provides the exergy efficiency results for the 1G-AUT. Figure 6 presents the process irreversibilities in this platform. With respect to the destroyed exergy per litter of ethanol produced [kWh/l] in each subsystem of this route, it was found: Cleaning, preparation and extraction (milling unit) 2.523, Juice treatment (clarification unit) 0.375, Juice concentration (evaporation unit) 0.567, Fermentation 2.163, Distillation 0.208, Dehydration 0.063, Condensate Tank 0.20, Sugar production 1.173 and Cogeneration system 10.39.

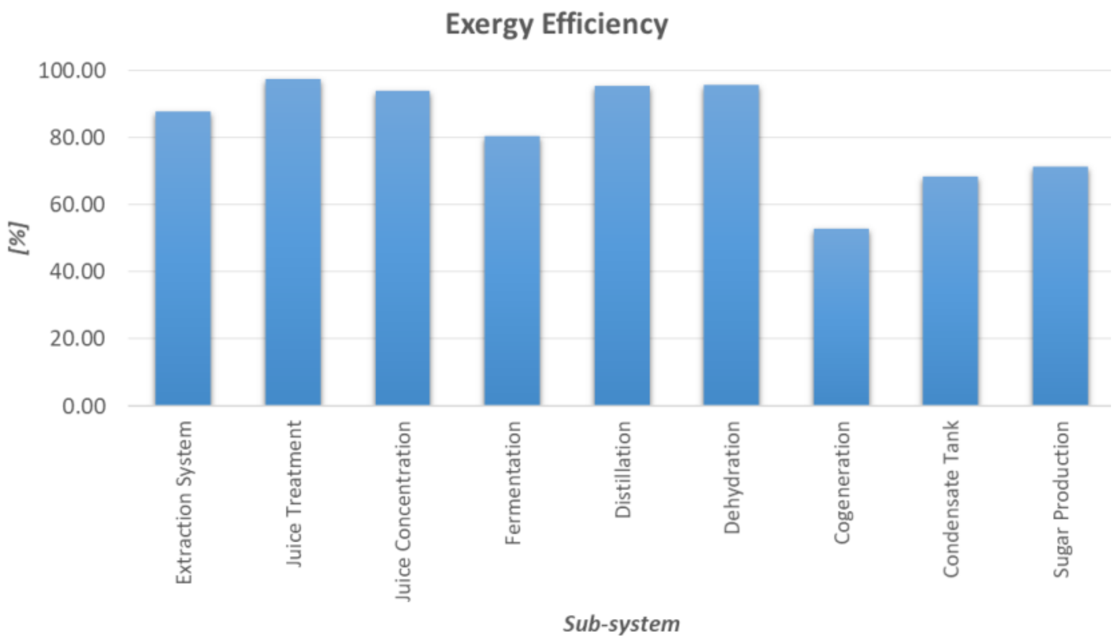

Figure 5: Exergy efficiency of the components of 1G-ANX.

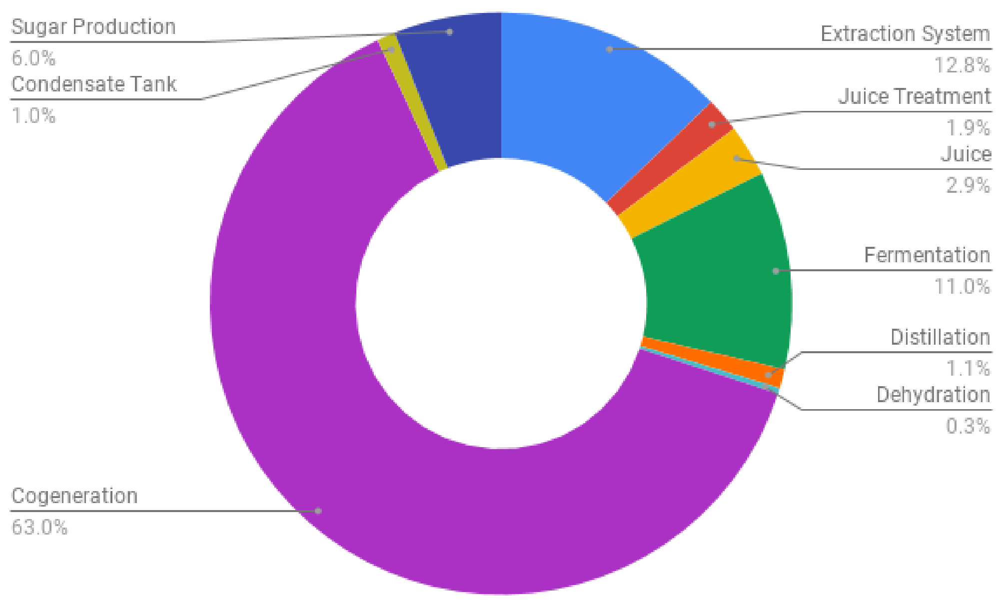

Figure 6: Percentage destroyed exergy of the 1G-Annex system.

4.3 Economic Analysis

Concerning the economic analysis, the techno-economic assessment results of the 1G-ANX and 1G-AUT systems were summarized in Figure 7. It is important to notice that the economic assessment is focused on the calculation of the total capital expenditure (CAPEX) of each configuration.

Hence, the CAPEX for the annexed plant (1G-ANX) was determined as 344 US$ million, and for the autonomous distillery (1G–AUT), its system was estimated as 338 US$ million. Fig. 7 shows the percent estimated of the capital expenditure components for each sub-systems.

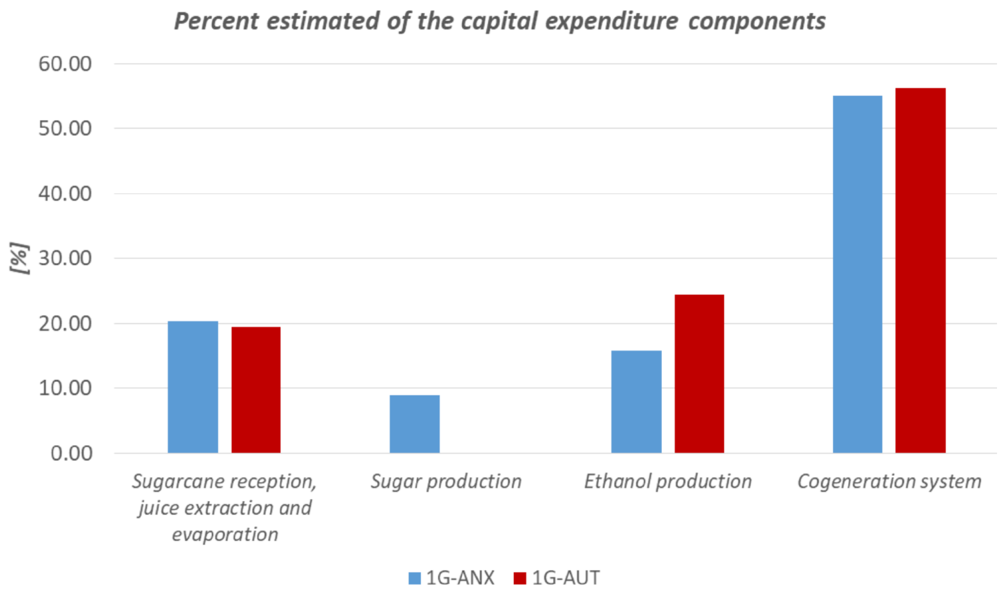

Figure 7: Percent estimated of the capital expenditure components.

4.4 Overall performance of the systems

Lastly, in order to contrast the global performance of the 1G-AUT and 1G-ANX systems with the earlier findings reported in Table 3, the overall assessment for the sugarcane biorefineries focused on the technical, environmental and economic (exergetic base) issues is summarized in Table 4.

Table 4: Overall performance of the biorefineries configurations.

	1G-ANX	*1G-AUT*
Products		
Ethanol production [L/TC]	53.07	84.19
Surplus electricity [kWh/TC]	181.86	181.58
Sugar production [kg/TC]	50.28	0
Efficiencies		
Energy efficiency [%]	48.93	44.81
Exergy efficiency [%]	41.39	37.90
Average unitary exergy cost [kJ/kJ]	2.41	2.63
Destroyed Exergy		
Irreversibilities [kWh/TC]	961.27	1018.45
Specific destroyed exergy [kJ/kg]	3460	3666
Ratio [I/Bp]	*1.42*	*1.64*
CO_2 equivalent rate ($BCO_{2\,EE}$) [gCO_2/MJ product(s)]		
$BCO_{2\,EE}$ *(Product: Ethanol, EtOH)*	297.17	187.54
$BCO_{2\,EE}$ *(Products: EtOH + Electricity)*	187.50	137.08
$BCO_{2\,EE}$ *(Products: EtOH + Sugar + Electricity)*	125.38	137.08

It is noted that the BCO2 EE index was calculated in terms of the product(s) considered in the analysis. Highlighting the decrease of this index for the 1G-ANX system in 57%, when it is designed the joint production of ethanol, sugar and electricity. Thus, this information was used to evaluate the configurations performance according to technical, environmental and economic criteria, previously established.

5 Conclusions

The performance indexes allowed to determinate the global assessment for plants producing ethanol, sugar, and electricity. It must be underlined that the lignocellulosic material (bagasse and straw) in both configurations was addressed it for the cogeneration-CHP unit, looking for improving the electricity for the grid. Hence, this comparison also indicated that the main exergy losses take place in the sub-systems that exhibit the largest irreversibilities, the CHP unit, the juice extraction, and the ethanol fermentation section.
The techno-economic analysis was performed to assess the annexed plant (1G–ANX) and the autonomous distillery (1G–AUT) systems considering the estimation on capital expenditure. It is important to notice that the higher investments are related to the combined heat and power (CHP), sugarcane reception and ethanol production (juice extraction) sub-systems. For the overall assessment, the results of the economic analysis indicated that the annexed biorefineries processes (1G-ANX) have the higher capital expenditure.
As long as the overall energetic/exergetic efficiencies shown a better performance in the annexed plant than the autonomous distillery (1G-AUT) as a function of the destroyed exergy rate, highlighting for both plants the impact of the irreversibilities in the CHP system and its dependence on the performance of these biomass conversion technologies. Lastly, the exergy-based renewability indicator demonstrated that the sugarcane biorefineries were categorized as environmentally unfavorable. However, this calculation only referred to the industrial processing stage.

Acknowledgements

The authors acknowledge the São Paulo Research Foundation (FAPESP) for grants 2017/03091-8 and 2017/16106-3. In addition, this work was carried out within the framework of a FAPESP-BIOEN thematic project, process 2015/20630-4. The second author also would like to acknowledge the National Agency of Petroleum, Gas and Biofuels – ANP and its Human Resources Program (PRH/ANP Grant 48610.008928.99), and the Administrative Department of Science, Technology and Innovation – COLCIENCIAS. Lastly, the third author also acknowledges the National Research Council for Scientific and Technological Development, CNPq (grant 304935/2016-6).

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NOMENCLATURE

1G	First ethanol production process
ANX	Annexed plant
AUT	Autonomous distillery
CAPEX	Total capital expenditure
etOH	Ethanol
EOS	Equation of state
NRTL	Non-random two-liquid
TC	Ton of sugarcane
λ	Renewability exergy index
b	Specific exergy (kJ/kg)
b_i^{ch}	Standard chemical exergy
$\dot{B}$	Exergy flow rate (kW)
x	Mole or mass fraction
h	Specific enthalpy (kJ/kg)
LHV	Lower heating value (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (kPa, bar)
$\dot{Q}$	Heat rate (kW)
s	Specific entropy (kJ/kg K)
T	Temperature (C, K)
$\dot{W}$	Power, (kW)