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Exergetic, environmental and economic assessment of sugarcane first–generation biorefineries

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Abstract

First generation ethanol (1G) contributes to the majority of the ethanol produced worldwide, predominantly centered on corn and sugarcane. Nevertheless, several issues are regularly highlighted concerning the long-term sustainability of this technology, including its intensive water and land use, potential contamination of soils through the distillation residues, as well as the balance between fuel and food crops. Accordingly, in this study, a process design approach for biomass to ethanol production (1G ethanol technology) from sugarcane was performed by using Aspen Plus® software, based on the autonomous distillery (AUT, ethanol production) and the annexed plant (ANX, joint ethanol and sugar production) configurations. In addition, a performance comparison in respect to the exergy efficiency and the irreversibility as quality indicators of the conversion processes is carried out to identify potential improvements in the production facilities. Hence, the shortcomings of the techno-economic assessment of ethanol production can be overcome by using exergy efficiency as a suitable indicator for process performance. Moreover, the technical/sustainability aspects related to the process design of the sugarcane biorefineries are discussed in light of the renewability exergy index (λ). In general, the ANX plant has a saving in the process irreversibility rate of about 6 %, whereas the average unitary exergy cost is 10% lower (AUEC= 2.41 kJ/kJ), in contrast to the AUT distillery. Moreover, a techno-economic analysis was carried out to assess the annexed plant and the autonomous distillery systems, considering the estimated capital expenditure. The results indicated that the ANX biorefinery has higher capex than the AUT distillery. It is noted that the higher investments are associated with sugarcane reception, ethanol production (juice extraction) and the combined heat and power sub-systems. Concerning system performance, the ANX plant presented a better overall exergy efficiency, with 41.39 %. Although this multi-criteria analysis is applied to 1G ethanol technology; it may be well-matched for various biorefineries/bioprocesses as a methodology to support decision-making as concerns potential improvement, well ahead of detailed process design.

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

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1. Introduction

1G ethanol is produced commercially from edible crops using biochemical technologies. Therefore, the greater part of ethanol production in the world comes from sugar-containing crops, mainly sugarcane, sweet sorghum, and sugar beets [1]. These crops contain high amounts of sugars that can be directly extracted and fermented into ethanol. Sugarcane is to date the most effective raw material for ethanol production, especially because of the low utilization of fossil energy during sugarcane processing [1]. US and Brazil stand out as the first- and second-largest producers of ethanol in a production model based on corn and sugarcane, respectively. Around 58 billion of liters of ethanol were produced in the US in 2016 [2], while 670.6 million tons of sugarcane were processed into 38.9 million tons of sugar and about 28 billion of liters of ethanol in Brazil in the same year [3].

The techno-economic assessment of the ethanol production from sugarcane is part of an extensive research field around the world. In this regard, various Brazilian insti-

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tutions have analyzed different configurations of industrial biorefineries including ethanol and sugar mills (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 autonomous distilleries that focus exclusively on the ethanol production [9]. Regarding the exergetic assessment of these systems in the Brazilian framework, some important studies have been reported in the literature 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].

Other studies dealt with the integration of the production of first and second generation ethanol through the conversion of lignocellulosic residual materials from the supply chains, looking to improve the ethanol yield rate (Ensinas et al. [14]; Dias et al. [15]; Bonomi et al. [16]). Accordingly, this study deals with the biochemical conversion of ethanol production from sugarcane in a Brazilian biorefinery scenario. General models of both an autonomous distillery (1G-AUT) and an ethanol and sugar production process, i.e. an annexed system (1G-ANX) were developed based on model configurations for typical plants [17]. Finally, economic, environmental and exergy analysis for both systems are thoroughly discussed.

2. Process description

In this work, data for the autonomous distillery and the annexed plant with a processing capacity of 4 million tons of sugarcane (TC) per season, recovering 50% of sugarcane straw with a 30 wt. % moisture content, are considered. The processes for the sugarcane distillery and the annexed plant were separated into representative control volumes, namely:

- Extraction System: In this stage, sugarcane bagasse is obtained. Bagasse represents a readily available by-product present in a suitable condition for burning in steam boilers. Two main devices can be normally employed to perform this operation: mechanical mills and diffusers. A thorough comparison between milling and diffusion systems in the sugarcane industry is presented in the work of Palacios-Bereche et al. [18].
- Juice Treatment: In this process, the raw juice from the extraction system is treated to eliminate non-sugar impurities, using compounds like Sulfuric acid-H_2SO_4, Ammonium hydroxide-NH_4OH (nutrients), Phosphoric acid-H_3PO_4 and Calcium Oxide-CaO. During this step, the juice is heated by using vegetable steam produced by a multiple-effect evaporator.
- Sugar Production: In this block, boiling, crystallization and drying processes of the molasses are carried out. The aqueous sugar solution, also called 'syrup', is later used to produce ethanol by yeast fermentation. Meanwhile, the sugar extracted by the centrifuges has a high level of moisture. Accordingly, it must undergo a drying procedure before packing.

Table 1: Main parameters used in the simulation models. The technical parameters of this table are based on [19–21]

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-CHP Unit	
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}

- Ethanol Production: This section includes alcoholic fermentation, distillation, rectification and dehydration steps. The Melle-Boinot fermentation process is the method typically used in Brazilian distilleries. The alcohol in the broth is recovered by distillation, which utilizes distinctive boiling points of the volatile substances present to separate them [5]. As the ethanol and water mixture forms an azeotrope with a concentration of about 95 wt%, traditional distillation is first used to provide hydrated ethanol, then alternative separation procedures are required to supply anhydrous ethanol. Those techniques include azeotropic and extractive distillation and molecular sieves [15].
- Combined Heat and Power (CHP): This sub-system is responsible for supplying the electro-mechanical requests of the sugarcane mill. Therein, the bagasse is burned and the energy is recovered in the boilers and heat recovery steam generators in the utility plant to increase steam for use in the extraction-condensation steam turbines. The values of the main operating parameters of the process that are representative for standard mills in Brazil are specified in Table 1 [22]. Fig. 1 displays a diagram of the flowsheet of the combined ethanol, sugar and electricity production considered in

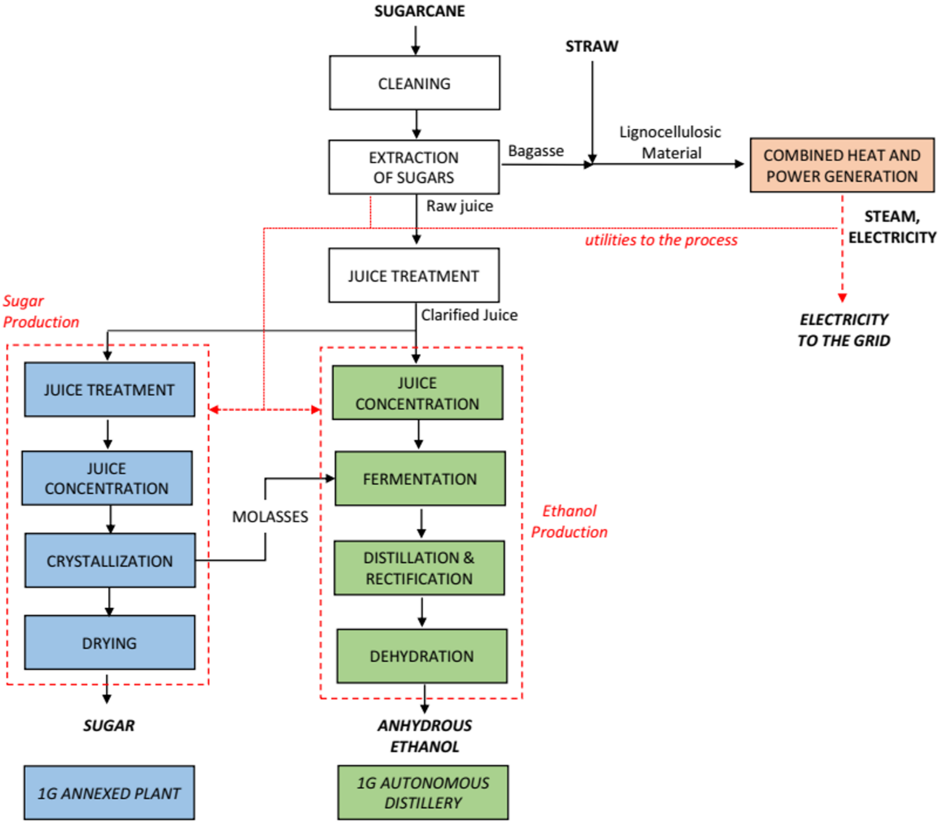

Figure 1: Process flow diagram of the first generation ethanol production process and electricity generation in the annexed and autonomous sugar cane mills

the analyses.

3. Methodology

Mathematical models along with data reported in the literature are used to simulate the steady state operation of two industrial plants producing either (i) ethanol, sugar and electricity (annexed plant, 1G-ANX) or (ii) ethanol and electricity only (autonomous distillery, 1G-AUT).

Fig. 2 shows a diagram of the design methodology for the assessment of these biorefinery configurations.

3.1. Modelling Approach

The models of the sugarcane biorefineries are founded on the calculation of the steady-state mass, energy, and exergy balances, according to Eqs. 1, 2 and 3, respectively for each one of the control volumes composing the mill.

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

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

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

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 irreversibility (exergy losses).

3.2. Process Simulation

The process simulation is carried out by using Aspen Plus® V8.6 software. As process streams in ethanol plants are complex, multi-component and multiphase systems, the non-random two-liquid (NRTL) was the thermodynamic method utilized in the simulation for the calculation of activity coefficients within the liquid phase. Meanwhile, the behavior of the vapor phase was assumed as ideal to define the thermo-physical properties of the flows present in the system.

Otherwise, the NRTL-HOC (Hayden-O'Connell) method was utilized for vapor-phase estimation when the concentration of acetic acid and other carboxylic acids is substantial, similar to the case of the fermentation and distillation steps, as suggested by Bonomi et al. [22].

In the utility plant, an enhanced SRK equation of state (EOS) found on the semi-empirical Redlich-Kwong with Soave modifications was adopted due to it being suitable for high temperature gases. Furthermore, STEAMNBS mode was utilized for the steam streams, as it accurately represents pure water and steam for an extensive range of temperatures and pressures [23].

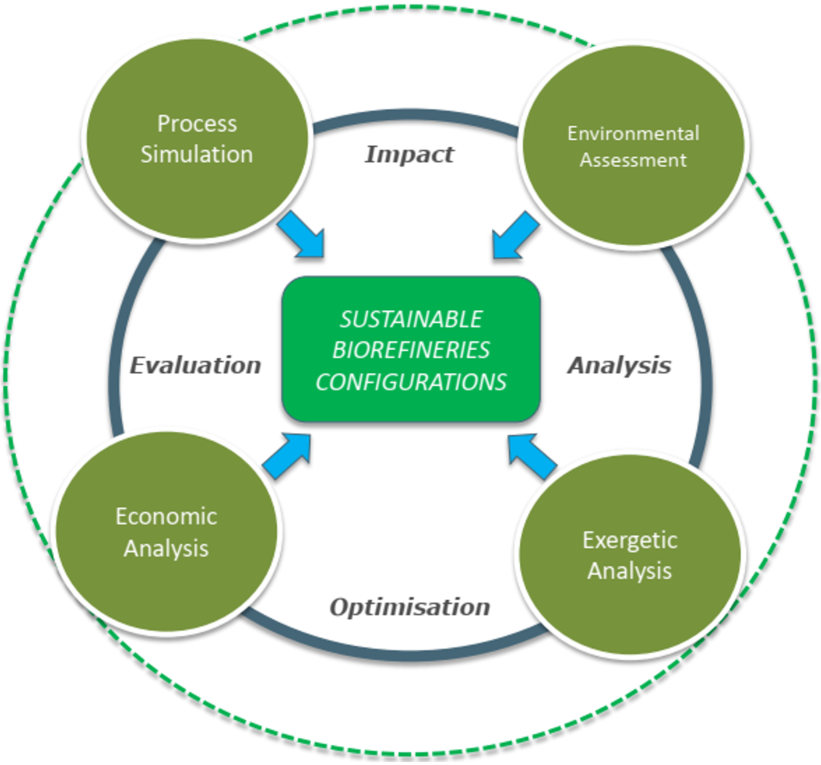

Figure 2: Assessment methodology for the sustainable configurations of the biorefineries

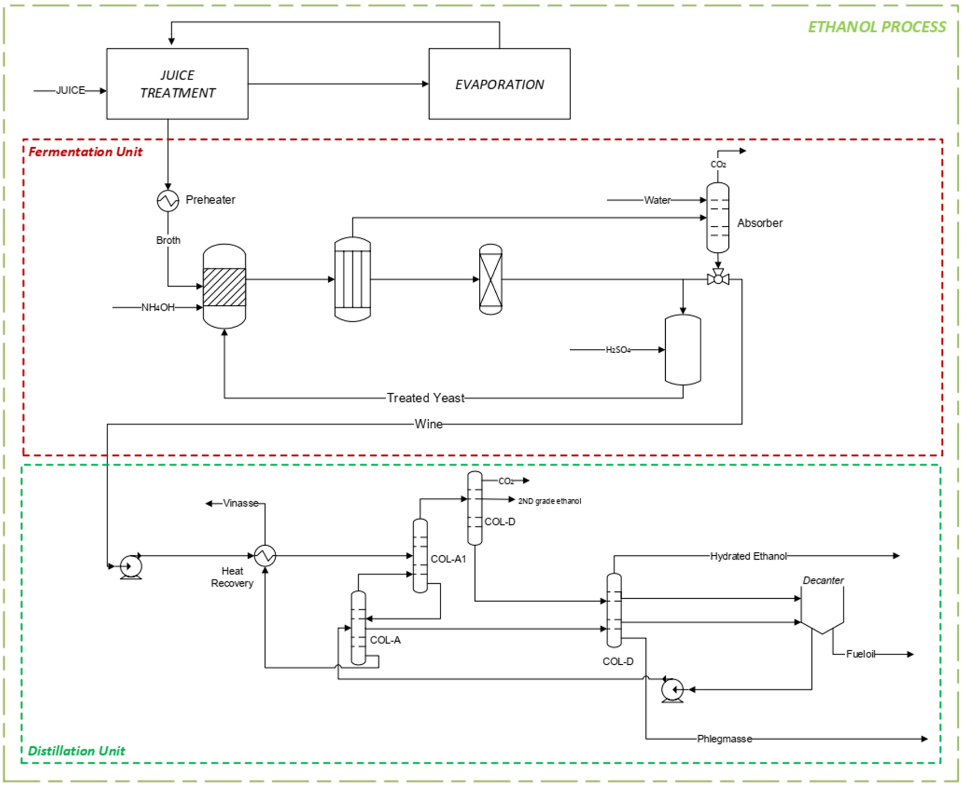

Figure 3: Process flow diagram of the ethanol production process

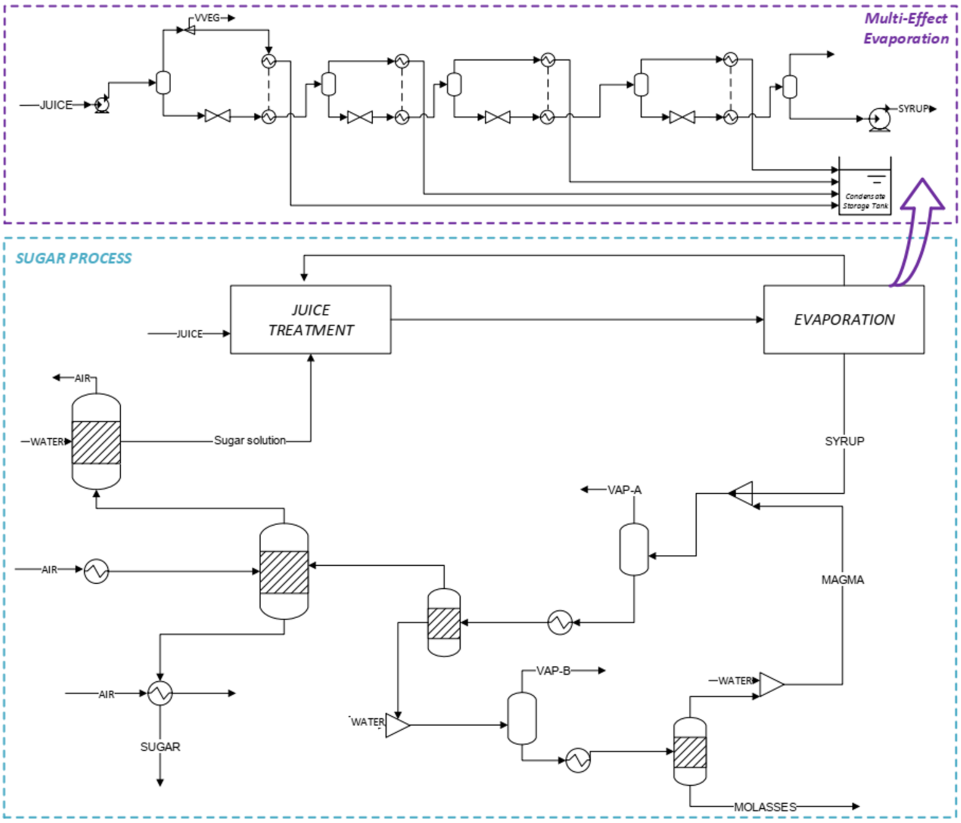

Figure 4: Process flow diagram of the sugar production process

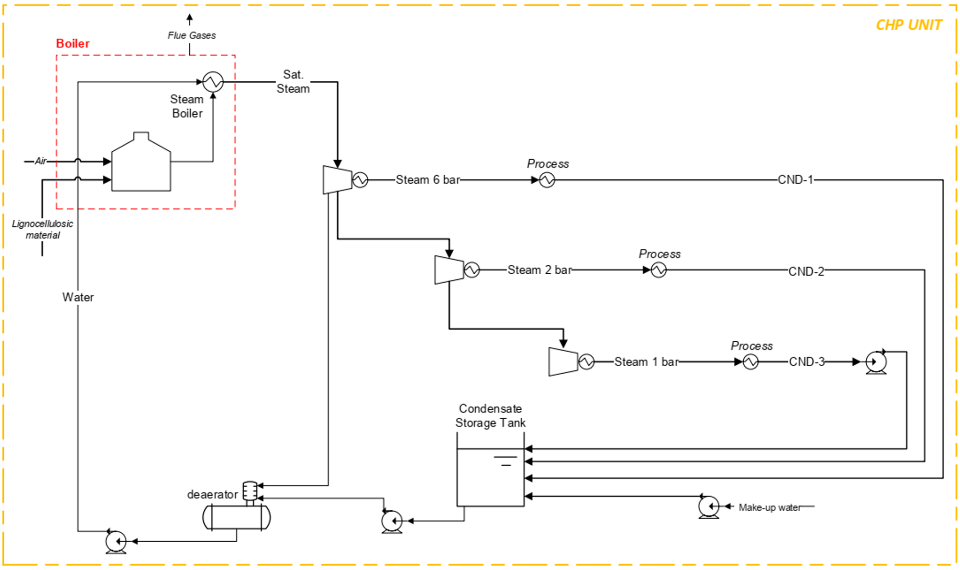

Figure 5: Process flow diagram of the Combined Heat and Power-CHP unit

Regarding the process design, Fig. 3 shows the flowsheet of the subsystems involved in the ethanol production process. In addition, Fig. 4 displays the processes flow diagram of the subsystems comprised in the sugar production. Lastly, Fig. 5 presents the simplified scheme of the cogeneration plant-CHP unit considered in this study.

3.3. Exergy Calculation

The exergy approach, which combines the First and Second Law of Thermodynamics, was applied to evaluate the performance of the ANX plant and the AUT distillery. The exergy concept is defined as the maximum work that can be gained as a consequence of reversible processes from a thermodynamic system that interacts only with the components of the environment until dead state equilibrium is achieved [24]. The ambient conditions are considered as T_0= 298.15 K and P_0= 1 atm, respectively. The exergy reference environment is composed of representative substances that exist in equilibrium, by means of which the standard chemical exergy of the remaining chemical compounds can be calculated [1]. Accordingly, Table 2 shows the standard chemical exergy of the compounds used in the exergy assessment. The exergy analysis throughout this work was conducted by using the data of mass flow rate, pressure, temperature, entropy, enthalpy, and composition of each stream obtained in Aspen Plus®. For convenience, the physical and chemical exergy sum called total exergy (BT) was used for the total specific exergy calculation as indicated by Szargut [24].

Thus, the kinetic and potential exergy are assumed to be negligible compared to the terms of physical and chemical exergy. The physical (B_{ph}) and chemical (B_{ch}) exergy were determined according to Eq. (4) and Eq. (5).

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

where: H—Enthalpy flow rate at P, T, kW; S—Entropy rate/flow rate at P, T, kW/K; T_o—Temperature at the reference state, K; H_o—Enthalpy flow rate at Po, To, kW; S_o—Entropy rate/flow rate at Po, To, kW/K.

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

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 its standard chemical exergy. The b_i^{ch} of the compounds was estimated by using Szargut's proposed methodology, 21, as indicated for lignocellulosic biomass in Silva Ortiz and Oliveira Jr., [26, 27]. Furthermore, the b_i^{ch} for compounds not offered in the specialized literature of the exergy field was determined according to the method proposed for technical fuels primarily based on atomic ratios and the net heating values of the substances [24]. For instance, for dry organic substances contained in solid fuels consisting of Carbon (c), Hydrogen (h), Oxygen (o) and Nitrogen (n) with a mass ratio of oxygen to carbon less than 0.667, the subsequent expression was utilized with regard to mass ratios. According to Kotas [25] the accuracy of Eq. (6) is estimated to be better than ± 1 %.

$$\varphi_{dry} = \frac{1.0438 + 0.1882\frac{h}{c} - 0.2509\left(1 + 0.7256\frac{h}{c}\right) + 0.0383\frac{n}{c}}{1 - 0.3035\frac{o}{c}} \tag{6}$$

where c, h, o and n are expressed in mass fractions.

3.4. Performance Indexes

Exergy serves not only for outlining indicators to evaluate the overall chemical process performance, but also as an indicator of environmental impact. For instance, it can be considered as a degree level of the quality of the energy embodied in products, by-products and residues in environmental/system conditions. Several technical indexes were proposed to evaluate the performance of the sugarcane biorefineries based on thermodynamic indicators, as explained in more detail below.

i) Energy efficiency is defined as the ratio between the useful output (Products = ethanol + sugar + suplus electricity) and the input (Resources=sugarcane + straw) of the overall energy conversion process, Eq. (7).

$$\eta_E = \frac{\sum(\dot{m}\ .\ LHV)_{products} + \dot{w}_{net}}{\sum(\dot{m}\ .LHV)_{resources}} \tag{7}$$

ii) Exergy efficiency is expressed by the relation between the exergy of the products and the exergy of the resources, as indicated in Eq. (8).

$$\eta_B = \frac{\sum \dot{B}_{products}}{\sum \dot{B}_{resources}} \tag{8}$$

iii) Renewability exergy index (λ): This indicator considers the exergy related to the useful products ($B_{productsor}B_{by-products}$) of a given energy conversion process, the destroyed exergy or total process irreversibilities ($B_{destroyed}$), the exergy linked to fossil fuels (B_{fossil}), the exergy needed for disposal of the wastes, and the exergy associated with environmental emissions, residues and untreated wastes.

According to Oliveira Jr. [28], depending on the λ value obtained from Eq. (9), it point out 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. Furthermore, increasing λ implies that the process is more environmentally friendly. Lastly, (iv) when $\lambda \rightarrow \infty$ it means that the process is reversible with renewable inputs and no wastes are produced [28].

$$\lambda = \frac{\sum \dot{B}_{products}}{\dot{B}_{fossil} + \dot{B}_{destroyed} + \dot{B}_{deactivation} + \dot{B}_{disposal} + \int \dot{B}_{emissions}} \tag{9}$$

$\dot{B}_{products}$ Exergy related to the useful outcomes and by-products,

$\dot{B}_{fossil}$ Exergy associated to the fossil fuels,
$\dot{B}_{destroyed}$ Process irreversibilities or destroyed exergy,
$\dot{B}_{deactivation}$ Exergy linked with the deactivation and treating wastes,
$\dot{B}_{disposal}$ Exergy flows rate related to waste disposal of the process,
$\dot{B}_{emissions}$ Exergy rate of wastes that are not treated or deactivated.

iv) Specific CO_2 equivalent emissions (CO_{2EE}): This index 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. (10).

$$CO_{2\ EE} = \frac{Global\ CO_{2equivalent\ emissions}}{B_{products}} \tag{10}$$

v) I/Bp Ratio represent the relation between the exergy destroyed and the exergy of the products in these processes, as given in Eq. (11).

$$I/Bp_{\ ratio} = \frac{Irreversibility}{\sum \dot{B}_{products}} \tag{11}$$

vi) Average unitary exergy cost (AUEC): Exergetic cost is a conservative value representing the external exergy that is needed to make an exergy stream available inside a particular productive process [29]. Consequently, the average unit exergy costs are a measure of the exergy consumption and cumulative irreversibility, which occur during the upstream processes to form a given exergy flow. Therefore, higher irreversibilities translate into higher unit exergy costs.

3.5. Economic Analysis

For the techno-economic assessment, the capital investment (capex) was estimated for each biorefinery configuration. Equipment sizing was characterized from the results of simulations in [17] and the financial aspects were estimated for each scenario following well-known approaches [30–32]. The purchase cost of most equipment was assessed from equipment cost databases, and adjusted by using correlations from literature, as in Turton [30] and Ulrich & Vasudevan [31] to detail the specific process pressures and material. The cost of distillation columns and decanters items were assessed via built-in cost models in the Aspen simulator. The purchase cost was corrected to 2017 using the Chemical Engineering Plant Cost Index (CEPCI 567.5), and the installation cost was estimated using suitable multiplication factors from the literature [30–32].

Regarding the biofuel production costs, total capital investments (TCI) is an important indicator. TCI is determinate centered on the state of technology development from several methodologies (i.e., rough, study, or approval estimations, all with different accuracies and therefore financial uncertainties). While approval estimations for commercial plants can frequently be applied (accuracy of ± 5–15 %), in the case of pilot plants or demonstration stage TCI is primarily founded on study estimations (accuracy of ± 20–30 %). As indicated by this, plant equipment costs are normally calculated by up- or downscaling for comparable technology (common scale factor of about 0.6–0.7). Furthermore, specific equipment set-up installation factors for biofuels are generally around 1.0–1.7 [33].

Moreover, the economic assessment considered the utilization of specialized materials, such as costly stainless steel, required by equipment operating under corrosive/heavy duty operating conditions. Concerning the exchanger details, the overall heat transfer coefficient, U, (W/m^{2}K) and the required exchanger area were obtained from the Aspen Plus results. Table 3 illustrates the principal assumptions and parameters adopted in the economic analysis of the design of the heat exchangers for the autonomous and annexed ethanol mills.

4. Results

In general, this work points out the relation between the exergy efficiency and the renewability exergy index associated with the process design of the autonomous and annexed plant ethanol configurations. Table 4 describes the operating conditions utilized in each biorefinery plant to calculate the λ index. It was found that the ANX plant scores better in light of the performance indexes previously defined (Section 3), in contrast to the AUT distillery. It is noted that the specific CO_2 equivalent emissions index is similar for both plants. As concerns the values calculated for the λ index, the results indicated that both biorefinery processes (ANX and AUT) can be regarded as environmentally unfavourable processes, which means that the exergy of the products could not re-establish the environment to the conditions prior to the occurrence of the process (Tab. 4). Thus, with reference to the exergy values of the products and by-products of these systems, it is evidenced that the renewability of the production processes may not always be assured, even for alternative low-carbon fuel production routes such as that of sugarcane ethanol.

4.1. Exergetic analysis of sugarcane-based biorefineries

A comparative exergy analysis based on technical data reported for typical 1G configurations is presented in Table 5. The traditional 1G plant corresponds to an annexed plant producing sugar and ethanol (distribution 50% sugar, 50% ethanol). Several systems of the CHP unit, namely, Backpressure, Condensing/Extraction steam turbines for the steam generation at different levels have been described.

Irreversibility was obtained by applying the exergy balance expression introduced in Eq. (3) whereas exergy efficiency performance η_B was calculated by using Eq. (8). In addition, the relation between the irreversibility ($\dot{I}$) and the exergy of the products (BP) for these configurations was determined (I/Bp Ratio) by Eq. (11). The specific exergy values of the inputs considered were: Sugarcane 5130 kJ/kg, Straw 16725 kJ/kg, and Bagasse 9667 kJ/kg. Regarding the exergy of the products, the values adopted were: for sugar 17479 kJ/kg and for ethanol 27042 kJ/kg, respectively. For comparison, the selected configurations were considered an autonomous distillery processing 2,000,000 TC/y, as it represents standard mill capacity in São Paulo State, Brazil. In this study, an optimized process with a processing capacity of 4,000,000 TC/y was explored. For this reason, the irreversibility ($\dot{I}$) was reported in terms of electricity per tons of processed sugarcane (kWh/TC) to verify the effect of the scale factor on the systems.

In the 1G-AUT case, the results obtained in this work are comparable/equivalent to previous studies that adopted similar parameters for the pressure and temperature of boiler live steam. For instance, Albarelli et al. [7] using a 1G-AUT configuration (65 bar / 480) achieved an exergy efficiency of the plant equal to 37.6 % and I/B$_p$ Ratio=1.66. Palacios-Bereche [12] report an autonomous distillery with exergy efficiency of 28.4% and I/Bp Ratio=1.41. For the annexed distillery, Albarelli et al. [7] reached an exergy efficiency of the system equal to 44.3% and I/Bp Ratio=1.26.

4.2. Exergetic analysis of the different components of the sugarcane biorefineries

Fig. 6 indicates the exergy efficiency of the different subsystems of the 1G-AUT configuration. Furthermore, Fig. 7 shows the share of the exergy destruction of each process in the biorefinery. One of the largest sources of specific exergy destruction, kWh/l corresponds to the cleaning, preparation and extraction (milling unit) processes (1.634), followed by juice treatment (clarification unit) (0.506), juice concentration (evaporation unit) (0.114), fermentation (2.158), distillation (0.566), and dehydration (0.075), as well as the condensate tank (0.054). However, the lion's share of the specific exergy destruction corresponds by far to the cogeneration system (8.00).

On the other hand, Fig. 8 provides the calculated results of the exergy efficiency for the 1G-ANX configuration. Fig. 9 presents the contribution of each subsystem to the overall exergy destruction in the annexed plant. Analogously to the previous configuration, the specific exergy destroyed per liter of ethanol produced, kWh/l in the 1G-ANX route were calculated for each sub-system: 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) and dehydration processes (0.063), as well as the condensate tank (0.20), sugar production (1.173) and the cogeneration system (10.39).

4.3. Economic Analysis

Concerning the economic analysis, the results of the techno-economic assessment of the 1G-ANX and 1G-AUT systems are summarized in Fig. 10. It is important to note that the economic assessment is focused on the calculation of the total capital expenditure (capex) of each configuration. It has been determined for the annexed (1G-ANX) as US$345.3 million, and for the autonomous distillery (1G–AUT) as US$338.6 million, respectively. Fig. 10 shows the breakdown of the investment cost (or capital expenditure) of the most representative subsystems composing the autonomous and annexed biorefineries.

The capex calculation involves the equipment of the different sub-systems (i.e. devices for Sugarcane reception, juice extraction and evaporation, ethanol production (fermentation, distillation/dehydration), sugar production (crystallization and drying) and CHP unit (utilities, steam, and electricity generation).

4.4. Overall performance of the systems

Finally, the overall performance of the 1G-AUT and 1G-ANX configurations was compared with the earlier findings given in Table 4. In addition, the global assessment for the sugarcane biorefineries focused on the multi-criteria approach is summarized in Table 6.

As can be seen, the CO$_{2EE}$ index was considered in terms of the product(s) involved in the analysis. Strikingly, there is a notable reduction in specific CO$_2$ equivalent emissions for the 1G-ANX system (57% lower) when compared to the autonomous biorefinery. Thus, the joint production of sugar, ethanol, and electricity, beneficially impacts the overall performance of the sugarcane refineries studied, as has been shown from the technical, environmental and economic (capex and AUEC, exergetic base) criteria proposed.

5. Conclusions

In this work, a techno-economic analysis was carried out to evaluate the annexed plant (1G–ANX) and the autonomous distillery (1G–AUT) systems in light of estimated capital expenditure. It must be pointed out that sugarcane reception, the combined heat and power, and the juice extraction sub-systems need higher investments. For the overall assessment, the outcomes of the economic analysis indicated that the annexed biorefineries processes required higher capital expenditure.

The multi-criteria approach based on the technical indexes determined the global assessment of the plants producing ethanol, sugar, and electricity. It is noted that the bagasse and straw (lignocellulosic feedstock) in each system was consumed in the biomass boiler in the CHP unit to produce the combined heat and power requirements of the plant, with the surplus electricity being exported to the grid. In addition, the performance comparison points out that the main irreversibilities take place in the sub-systems which show the highest exergy losses, namely, cogeneration, juice extraction and fermentation processes.

By applying the energy and exergy balances for both systems, the global energetic/exergetic efficiencies presented better performance in the annexed plant in contrast to the autonomous distillery as a consequence of the irreversibility rates. This highlights the effect of the destroyed exergy in the cogeneration unit and its dependence on the effectiveness of these biomass conversion pathways from 1G ethanol production. Furthermore, the exergy-based renewability indicator established that these configurations were categorized

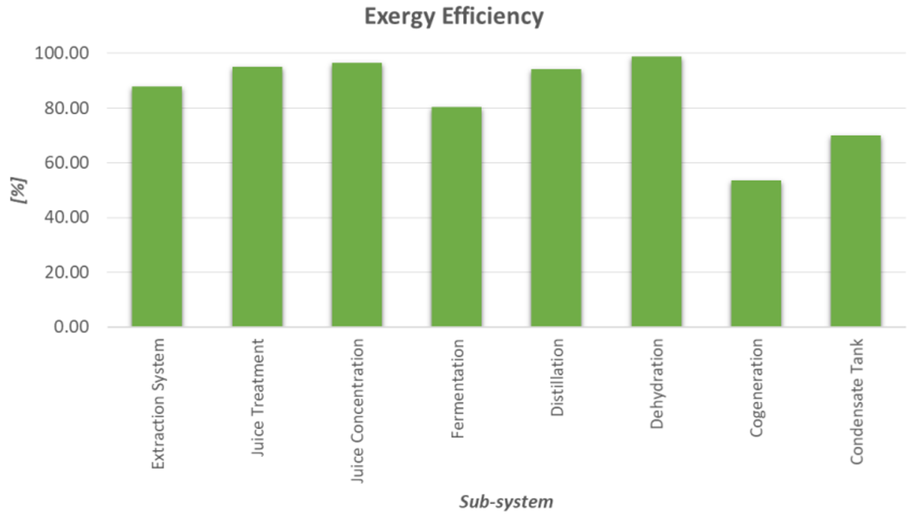

Figure 6: Exergy efficiency of the components of 1G-AUT configuration

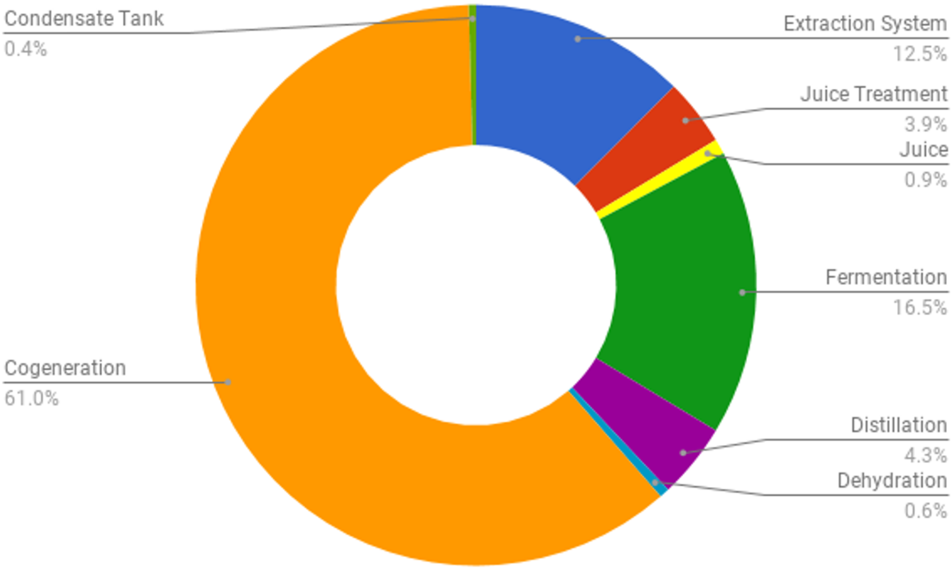

Figure 7: Breakdown of the destroyed exergy in the 1G-AUT system

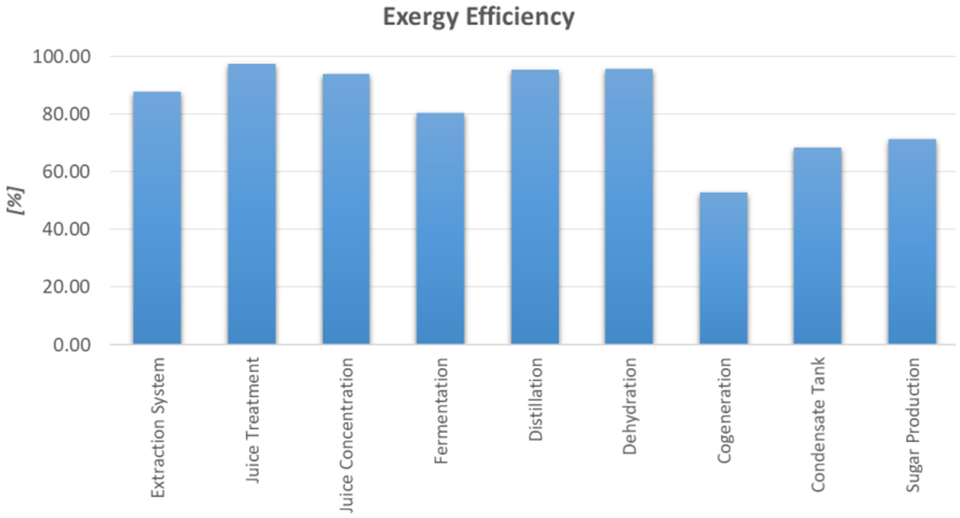

Figure 8: Exergy efficiency of the components of 1G-ANX

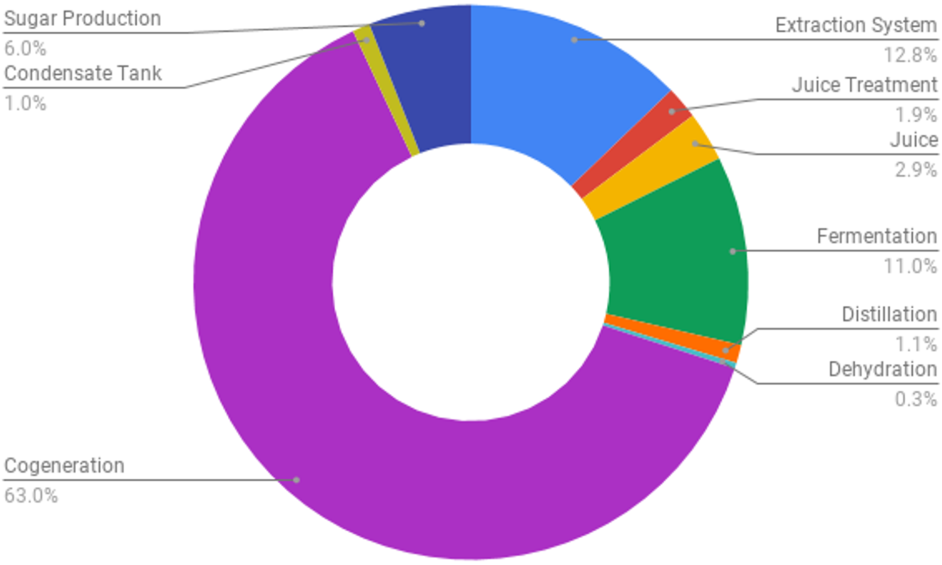

Figure 9: Breakdown of the destroyed exergy in the 1G-Annexed configuration

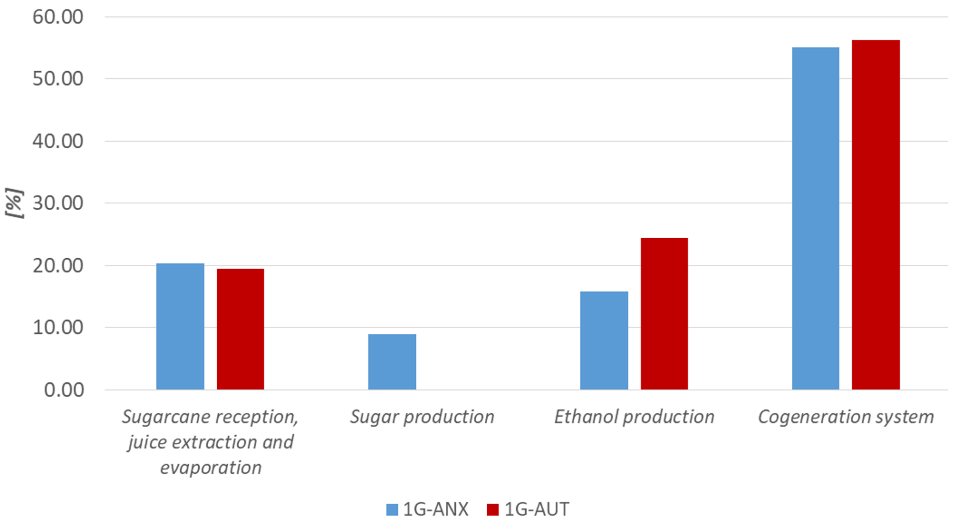

Figure 10: Breakdown of the investment cost/capital expenditure in the autonomous and annexed biorefineries

as environmentally unfavorable. Nevertheless, the λ index calculation was only referred to the control volume (systems boundaries) that involved the industrial processing stage of the sugarcane biorefineries.

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Nomenclature

1G	First ethanol production process
ANX	Annexed plant
AUT	Autonomous distillery
capex	Total capital expenditure
CO_{2EE}	Specific CO_2 equivalent emissions (exergetic base)
CV	Control volume
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 (kJ/kg)
$\dot{B}$	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)
ST	Steam turbine
T	Temperature (C, K)
$\dot{W}$	Power, (kW)

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Table 2: Standard chemical exergy of the compounds used in the exergy analysis

Chemical formula	Component	TYPE	$b^{CH}{}_{specific}$, kJ/kg	Reference
$C_6H_{10}O_5$	Cellulose	Solid	20997	**
$C_5H_8O_4$	Hemicellulose	Solid	21395	**
$C_{7.3}H_{13.9}O_{1.3}$	Lignin	Solid	28161	**
$Ca_3(PO_4)_2$	Calcium Phosphate	Solid	62	**
SIO_2	Silicon dioxide	Solid	32	**
SO_2	Sulfur Dioxide	Conventional	4892	*
CO_2	Carbon Dioxide	Conventional	452	*
C_2H_6O	Ethanol	Conventional	27152	*
$C_6H_{12}O_6$	Dextrose (Glucose)	Conventional	16556	*
$C_2H_4O_2$	Acetic Acid	Conventional	15121	*
$C_3H_8O_3$	Glycerol	Conventional	18521	*
$C_5H_{10}O_5$	Xylose	Conventional	12225	*
$C_5H_4O_2$	Furfural	Conventional	18545	*
$C_5H_{12}O$	Isoamyl alcohol	Conventional	35091	*
C_4H_6O	Succinic acid	Conventional	13629	*
$C_6H_6O_6$	Organic Acids	Conventional	1797	*
$C_{12}H_{22}O_{11}$	Sucrose	Conventional	17551	*
$Ca(OH)_2$	Calcium hydroxide	Conventional	725	*
CaO	Calcium Oxide	Conventional	1965	*
CO	Carbon monoxide	Conventional	9821	*
K_2O	Potassium Oxide	Conventional	4385	*
KCL	Potassium Chloride (Salts)	Conventional	259	*
NO	Nitric oxide	Conventional	2963	*
N_2	Nitrogen	Conventional	26	*
O_2	Oxygen	Conventional	124	*
H_2	Hydrogen	Conventional	117117	*
H_2O	Water	Conventional	50	*
H_2SO_4	Sulphuric Acid	Conventional	1666	*
NH_3	Ammonia	Conventional	19841	*

* Adopted values for b_{CHspec}. from Szargut et al. [24].

** Calculated by using the correlations proposed by Szargut and Styrylska linking the ratio of the standard chemical exergy and the lower heating value of the substances [25].

Table 3: Heat Exchangers Selection---Assumptions and parameters used in the economic analysis

ETHANOL PRODUCTION---1G-AUT Plant

Heat Exchangers UNIT		Type	Area, m^2	Q, kW	Purchased Equipment Cost, USD
HEX-1	BOILER	CHP	2580	618123	873000
HEX-2	ENERGY	CHP	252	24974	142000
HEX-3	ENERGY	CHP	1899	166508	602000
HEX-4	ENERGY	CHP	9778	245699	6790000
HEX-5	LIMING	JCE-TRT	1160	36204	301000
HEX-6	LIMING	ICE-TRT	1283	34635	301000
HEX-7	EVAPORATION	ETHANOL	965	6758	301000
HEX-8	FERMENTATION	ETHANOL	696	15377	238000
HEX-9	DISTILLATION	ETHANOL	752	29320	259000
HEX-10	DISTILLATION	ETHANOL	280	6987	142000
HEX-11	MOLECULAR SIEVE	ETHANOL	321	21854	160000
HEX-12	MOLECULAR SIEVE	ETHANOL	101	7124	92000
HEX-13	MOLECULAR SIEVE	ETHANOL	331	17189	160000

SUGAR PRODUCTION---1G-ANX Plant

Heat Exchangers MGT		Type	Area, m^2	Q, kW	Purchased Equipment Cost, USD
HEX-1	LIMING	ICE-TRT	420	17240	176000
HEX-2	LIMING	ICE-TRT	639	16741	228000
HEX-3	CLARIFICATION	ICE-TRT	494	702	183000
HEX-4	EVAPORATION	EVAP	2305	26691	602000
HEX-5	EVAPORATION	EVAP	1982	29097	602000
HEX-6	EVAPORATION	EVAP	513	31518	194000
HEX-7	EVAPORATION	EVAP	85	35152	92000
HEX-8	SUGAR DRYING	SUGAR	42	769	74700
HEX-9	SUGAR DRYING	SUGAR	15	447	61100
HEX-10	CRYSTALLIZATION	SUGAR	11	640	61100
HEX-11	CRYSTALLIZATION	SUGAR	17	362	62900

Table 4: 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 Irreversibility (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

Table 5: Comparison of the exergetic assessment of the 1G ethanol plants in this work and reports from the literature.

Description	Configuration	Superheated steam, bar/°C	η_B, %	$\dot{I}$ kWh/TC	Ratio I/Bp
[a]Rankine without straw (Condensing ST)	1G-AUT	80 / 500	44.59	778	1.24
[b]Base case (Back-pressure ST)	1G-ANX	22 / 300	36.10	940	1.77
[c]Case I (Back-pressure ST)	1G-AUT	100 / 530	35.65	756	1.32
[c]Case II (Back-pressure ST)	1G-ANX	100 / 530	40.11	772	1.20
[c]Case I-TI (Back-pressure ST, thermally integrated)	1G-AUT	100 / 530	33.85	592	1.09
[c]Case II-TI (Back-pressure ST, thermally integrated)	1G-ANX	100 / 530	38.10	546	0.89
[d]Base case---Ethanol distillery (Hydrated ethanol without surplus electricity)	1G-AUT	21 / 300	32.15	596	1.31
[d]Configuration A (Hydrated ethanol and surplus electricity)	1G-AUT	67 / 515	34.27	620	1.27
[d]Configuration B (Electrification of the milling)	1G-AUT	67 / 515	34.72	624	1.27
[d]Configuration C (Harvest, condensing ST)	1G-AUT	67 / 515	36.45	788	1.52
[d]Configuration D (Harvest, electrification of the milling and condensing ST)	1G-AUT	67 / 515	36.77	778	1.49
[d]Configuration E (Harvest, Multiple effect distillation)	1G-AUT	67 / 515	37.54	834	1.57
[e]Base case---Traditional Mill	1G-ANX	21 / 300	43.50	646	1.34
[e]BPST---Back-pressure ST	1G-ANX	67 / 515	45.60	632	1.22
[e]CEST---Condensing-Extraction ST	1G-ANX	67 / 515	44.40	708	1.32
[e]SuSC---Supercritical Steam Cycles	1G-ANX	292 / 590	50.00	644	1.06
[f] Base case---Autonomous distillery	1G-AUT	65 / 480	37.58	880	1.66
[f] Joint production conventional process	1G-ANX	65 / 480	44.30	786	1.26
[g] Base case---Autonomous distillery	1G-AUT	67 / 480	28.4	848	1.41
In this study---Annexed plant	1G-ANX	65 / 485	41.39	961	1.42
In this study---Autonomous distillery	1G-AUT	65 / 485	37.90	1018	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].

Table 6: 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
System performance		
System energy efficiency, %	48.93	44.81
System exergy efficiency, %	41.39	37.90
Average unitary exergy cost, kJ/kJ	2.41	2.63
Destroyed exergy		
Irreversibility, MW	889	941
Specific destroyed exergy, kJ/kg$_{biomass}$	3460	3666
Economic assessment		
Capex, US$ million	345.3	338.6
Ratio, I/Bp	1.42	1.64
Specific CO_2 equivalent emissions (CO_{2EE}), gCO_2/MJ product(s)		
CO_{2EE} (Product: Ethanol, etOH)	297.17	187.54
CO_{2EE} (Products: etOH + Electricity)	187.50	137.08
CO_{2EE} (Products: etOH + Sugar + Electricity)	125.38	137.08