Exergy and economic assessment of renewable electricity generation from sugarcane straw for improved efficiency of sugarcane biorefineries

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Abstract: This work focuses on the revamp of existing sugarcane biorefineries and cogeneration units by using those byproducts, aiming to increase the selling of surplus electricity. The analysis allows identifying potential improvements in the sugarcane cogeneration plants. Simulation processes are employed to denote incremental modifications related to sugarcane straw recovery achieved in the harvesting systems. The results show that the straw recovery through harvesting systems may increase the surplus electricity by up to 30% when sugarcane biorefineries consider the maximum straw recovery fraction. Moreover, the increment in the exergy cost of the straw gathering influences the extended exergy efficiency of the cogeneration unit and, consequently, the entire sugarcane biorefinery. In brief, the capitalisation on sugarcane residues may increase the contribution of this industry to the decarbonisation of the Brazilian electricity mix and increment of profits resulting from the negotiation of decarbonisation credits in the Brazilian sugarcane market.

Keywords: exergy analysis; sugarcane straw; irreversibility; biorefinery performance.

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1 Introduction

In the 2019/2020 sugarcane crop season, the sugarcane industry in Brazil processed 642.7 million tons of cane. It has been used for 95% of the ethanol production in Brazil (35.6 billion litres, 70.5% hydrated, and 29.5% anhydrous) while corn contributed with 5% (Kist et al., 2020). According to the Brazilian Sugarcane Industry Association (UNICA), the average productivity in the country increased to 76.30 tons per hectare (t/ha), despite the slight decrease in the crop area, mainly due to a sustained production volume, similar to the previous season (UNICA, 2020). Concerning the land use, the harvested area with sugarcane occupied 10 Mha in 2019, equivalent to only 1.2% of the land in Brazil (851 Mha) (CONAB, 2021).

Sugarcane represents the main energy resource for electricity generation in the sugar and ethanol production industry. One ton of crushed sugarcane generates roughly 250 kg of bagasse and 200 kg of straw and scraps. Hence, apart from supplying the amount of electricity demanded by the sugarcane plants, these residues can also generate surplus electricity that could be commercialised to the Brazilian interconnected system. Of the total electricity generation by sugarcane plants in 2019, which was 36.8 TWh, 61% was exported to the grid (Kist et al., 2020). In addition, the Brazilian electricity generation from solid biomass represented a share of 8.4% in the national electricity supply in 2019 (UNICA, 2020). According to UNICA, Brazil remains the largest sugar producer, reaching 29.8 million tons of sugar per year (Kist et al., 2020).

Governmental policies on biofuel utilisation by passenger vehicles have promoted the increase of ethanol production and, since 2015; the mixture of 27% ethanol (E27 blend) to gasoline is required by law (UNICA, 2020). Thus, compared to the last decade, the projections for the next ten years in the Brazilian sugarcane supply chain point to a sharp growth in ethanol and sugar production and power generation. This circumstance is enhanced by the RenovaBio program, a policy introduced in 2018 to increase energy efficiency and reduce the CO_2 emissions by this sector (Klein et al., 2019). Brazilian RenovaBio program aims to cut down about 10% of greenhouse gas (GHG) emissions in the transport energy mix, contributing significantly to the nationally determined contribution (NDC) target of 43% less GHG emissions by 2030 (Instituto E+ Transição Energética, 2021; UNICA, 2020). Therefore, it is expected a growing negotiation of decarbonisation credits (CBios) in the stock market and a rise in the number of certifications for biofuel producers (Carvalho et al., 2021; Gonçalves et al., 2021).

In this context, sugarcane-derived electricity is a key driver to the diversification, the gain in flexibility, and the sustainable development of the ethanol and sugar industry. For that reason, special attention was given in the last year to the retrofit of biorefinery systems and the characterisation of raw materials that could be used as input for the cogeneration unit. Currently, the most promising biomass resources and technological approaches reportedly focus on the capitalisation on modern bio-refinement of forestry residues (Teixeira Coelho et al., 2021), which can be utilised to replace fossil fuels in part or totally (Nakashima et al., 2020; Ribeiro Domingos et al., 2020). For instance, the potential of the Brazilian biogas, which could be used for electricity generation (88.5 GWh/y or around 18% of the Brazilian electricity consumption in 2019) or fuel production (21.8 billion m^3 of biogas/y or close to 30% of Brazilian consumption in 2019) (ABiogás, 2021).

According to the Sugarcane Renewable Electricity (SUCRE/CNPEM) project, the bioelectricity generation in Brazil could be increased from 22 TWh up to 104 TWh, by recovering 50% of the produced straw and improving the performance of the cogeneration system with no additional land requirement. This alternative surplus power could potentially supply 78% of the domestic electricity demand and mitigate 11% of the GHG emissions of the energy sector (Leal and Hernandes, 2020). Thus, improving the energy utilisation in the mills for combined heat and power (CHP) production is a key step towards the exploitation of this potential. An optimised plant configuration is characterised by the integration of more efficient boilers, extraction-condensation steam turbines, and mill electrification, aiming to reduce steam consumption and to produce, at least, 100 kWh of electricity surplus per ton of sugarcane processed (Bonomi et al., 2016; Cardoso et al., 2018). Advanced utility configurations also explore the use of other raw materials in energy systems of biorefineries (Ribeiro Domingos et al., 2020). This is an interesting aspect because it provides a window of opportunities to increase the energy efficiency and the biorefinery profits through the CBio market towards optimised ethanol production processes, reduced costs, and minimised environmental impact.

Although considerable research has been devoted to the optimisation of such cogeneration systems, less attention has been paid to the integral assessment of these technologies based on complementary key performance indicators (KPIs) involving economic and technical dimensions. Accordingly, this study focuses on the retrofit of existing sugarcane cogeneration systems, aiming to increase the commercialisation of surplus electricity, considering partial or total straw recovery and its operation in the season periods based on recent field studies performed in Brazilian conditions. A comparison between the performance of an autonomous and an annexed sugar cane mill is carried out in terms of:

1 the global exergy efficiency

2 the average unit exergy cost

3 the irreversibility rate as thermodynamic indicators to identify potential improvements in existing Brazilian sugarcane biorefineries.

Furthermore, this paper briefly discusses the potential of the CBIOs associated with sugarcane ethanol production and estimates additional revenues related to the decarbonisation credit market.

2 Processes description

Two scenarios, namely, first-generation ethanol production in an autonomous distillery (1G-AUT, *only ethanol production*) and an annexed plant (1G-ANX, *combined ethanol and sugar production*) are studied. Both scenarios consider a milling capacity of 4 million tons of sugarcane (TC) during 200 days/y. For the sake of increased efficiency and power throughput, the recovery of the sugarcane straw produced in the field is also considered. In the sugarcane mill, sugarcane is firstly cleaned and crushed, wherein 125 kg of bagasse (dry basis) are produced per TC. The lower heating value (LHV) of the bagasse with 50% wt. moisture content is 7.5 MJ/kg. In addition, a fraction (30%–100%) of the sugarcane straw (i.e., tops and leaves ~140 kg straw/TC dry basis) can also be transported to the cogeneration unit to increase the surplus electricity. The LHV of straw with 30% wt. moisture content is 11.5 MJ/kg.

Simulations of both 1G-AUT and 1G-ANX models are developed based on key parameters reported for conventional mills (Bonomi et al., 2016; Palacios-Bereche et al., 2013; Silva Ortiz et al., 2019a). The processes involved in the sugarcane distillery and the annexed plant are grouped into representative control volumes, as illustrated in Figure 1.

In Figure 1, the lignocellulosic materials (e.g., bagasse and straw) are sent to the cogeneration unit (CHP), which converts these materials into steam and electricity. A steam cycle (high-pressure steam 65 bar and 480°C) with backpressure steam turbines is adopted to model the CHP unit. Straw utilisation rates of 30%, 50%, 65%, and 100% of the available lignocellulosic material in sugarcane fields are considered as input to the CHP unit of each system.

Figure 1 Main unit operations of the annexed and autonomous sugarcane biorefineries (see online version for colours)

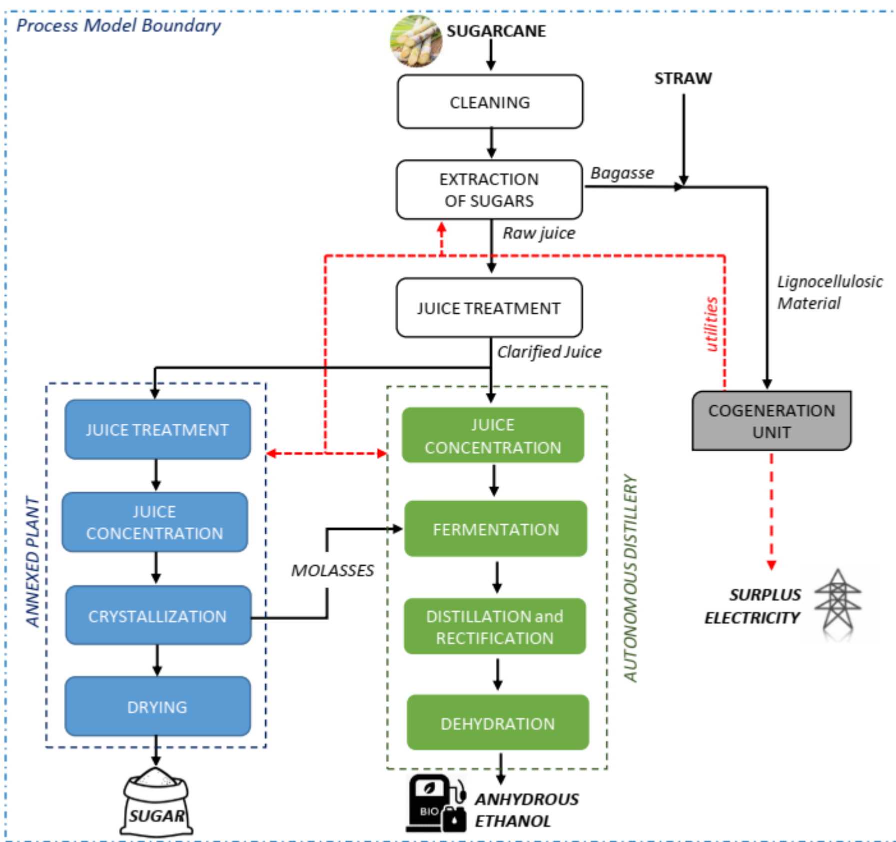


Table 1 gives the values of the main operating parameters for each process considering the typical Brazilian scenario. More details of the first-generation process descriptions can be found elsewhere (Bonomi et al., 2016; Palacios-Bereche et al., 2013; Silva Ortiz et al., 2019a). Moreover, Table 2 shows the summary of the operating parameters adopted in the simulation of the CHP unit.

Table 1 Summary of the operating parameters for 1G-AUT and 1G-ANX sugarcane plants

Parameters	*Value*
Biomass conditioning	
• Sugar extraction	
Sugar extraction efficiency	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
Syrup Brix	65°
Ethanol production	
• Fermentation	
Fermentation temperature	33°C
Conversion of sugars to ethanol	89.5%
Ethanol content in the beer	80 g L^{-1}
H_2SO_4 addition in yeast treatment (100% basis)	5 kg m^{-3}ethanol
• Distillation	
Ethanol content in vinasse and phlegmasse	< 200 ppm
Hydrated ethanol purity	93% wt.
Feed temperature	150°C
Steam pressure	6 bar
Ethanol recovered as a final product	81.4%
Anhydrous ethanol purity	99.6%wt.
Sugar production (crystallisation 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

From the agricultural system perspective, a key factor associated with bagasse and straw recovery is the transportation distance of the biomass to the CHP conversion unit, since this logistic aspect is linked with the economic feasibility of the project. To quantify this effect, a typical distance of 50 km was adopted (Telini et al., 2021; Watanabe et al., 2020).

Further details about the agricultural and industrial aspects involved in the electricity production from sugarcane straw can be found elsewhere (Bonhivers et al., 2021; Sampaio et al., 2019; Watanabe et al., 2020).

Table 2 Main parameters for the cogeneration system

Parameters	*Value*
Pressure of the boiler system	65 bar
Steam temperature	485°C
Boiler efficiency (*LHV basis*)	87.7%
Turbine isentropic efficiency	85%
Generator efficiency	98%
Electricity demand of the processes	30 kWh TC^{-1}
Steam demand of the processes	500 kg TC^{-1}

Sugarcane straw can be gathered, processed, and mixed into the residual bagasse in the cogeneration unit to increase the potential of surplus electricity generation. However, most of the biomass boilers in sugarcane mills were originally designed to operate with bagasse exclusively. Thus, special attention should be given to the physicochemical properties of straw (i.e., density and particle size distribution) to avoid affecting boiler performance. Nevertheless, the assumptions used in the present study are based on a previous study that assessed the mixture of straw and bagasse used as fuel under industrial conditions (the SUCRE project by Leal and Hernandes, 2020).

3 Methods

In this section, the main methods and indicators used to evaluate the thermodynamic and economic performances are described. The exergy analysis is carried out using data of mass flow rates, pressures, temperatures, and other thermodynamic properties such as entropy, enthalpy, and composition of each stream, obtained from process simulation using Aspen Plus (v.8.8) (Aspentech, 2019). An MS-Excel spreadsheet-based cost estimation tool is also employed to conduct the techno-economic analysis based on the process design approach for biomass first-generation (1G) ethanol production. More details on the processes simulation can be found in previous works of the authors (Silva Ortiz et al., 2019a, 2019b).

3.1 Exergy analysis

Exergy is the maximum potential of producing work from the interaction of a given substance or energy flow with the environment in which it is embedded, using only thermodynamically ideal (*reversible*) processes. Thus, as a combination of the First and Second Laws of Thermodynamics, the exergy concept accounts for both the quantity and the quality of the energy and sheds light on the potential to improve the energy conversion processes. The main concepts and applications of exergy analysis to several industries were synthesised by De Oliveira (2013) and Ptasinski (2016).

In this study, the total exergy of a mass flow encompasses the chemical B_{ch} and the physical B_{ph} exergy. As for the case of sugarcane biomass, the term B_{ph} is often neglected since biomass generally enters at the ambient conditions of pressure and temperature (T_o, P_o), whereas the term B_{ch} is calculated as specified in equation (1):

$$B_{ch_{biomass}} = \dot{m}_{biomass} \times \beta \times LHV_{biomass} \tag{1}$$

where the mass flow rate $(\dot{m})$ is expressed in *kg*/*h*, the *LHV* of biomass is given in *kJ*/*kg*; and β is the ratio between the chemical exergy to the LHV, which, in turn, can be calculated from the correlations reported for lignocellulosic material with an O/C ratio ≤ 2 (Szargut et al., 1988), according to equation (2):

$$\beta = \frac{1.044 + 0.0160\left(\frac{H}{C}\right) - 0.3493\left(\frac{O}{C}\right) \times \left(1 + 0.0531\left(\frac{H}{C}\right)\right) + 0.0493\left(\frac{N}{C}\right)}{1 - 0.4124\left(\frac{O}{C}\right)} \tag{2}$$

In equation (2), the mass fractions of carbon, hydrogen, oxygen, and nitrogen (i.e., C, H, O, and N) are known from the ultimate analysis of the biomass. Furthermore, the irreversibility rate associated with the exergy destruction in the industrial plant allows a thorough assessment of the actual system performance in terms of the deviation from the ideal conversion process.

The minimisation of exergy destruction can be used as a rational target for optimisation purposes. Thus, the exergy balance aids in computing the plantwide and component-wise irreversibility distribution. Equation (3) shows the exergy balance of a control volume operating in a steady state.

$$\sum B_{in} = \sum B_{out} + I \tag{3}$$

where $\sum B_{in}$ is the sum of the exergy inputs to the system (kW), $\sum B_{out}$ represents the sum of the exergy outputs from the system (kW) and *I* is the irreversibility rate within the process studied (kW).

Moreover, the average unit exergy cost (AUEC) can be adapted to measure the cumulative irreversibility and exergy consumption along with the energy conversion processes; hence, a higher irreversibility rate translates into higher unit exergy costs. It should be noted that the exergy cost indicator brings about a closer insight into the contribution of each product to the global plant efficiency based on the Second Law of Thermodynamics (Silva Ortiz et al., 2019b). According to equation (4), the average unit exergy cost c (kJ/kJ) of the ethanol production processes and the power generation can be determined as the weighted average of the exergy costs of both products:

$$AUEC_{process} = \frac{C_{ethanol} \times B_{ethanol} + c_{power} \times B_{power}}{B_{ethanol} + B_{power}} \tag{4}$$

3.2 Techno-economic analysis

A discounted cash flow analysis is applied to estimate the gross margin, the return on investment (ROI), the ethanol minimum selling price (MSP) and the payback time of the biorefinery scenarios in the Brazilian context, using the following assumptions:

1 building and start-up is performed in two years
2 project lifetime is 20 years with an operating factor of 200 days/y
3 no subsidies on capital investment costs
4 the nominal capacity is 100% during the first year of operation
5 100% equity
6 34% tax rate
7 ten-year linear depreciation
8 working capital is 2% of capital investment
9 R$3.79 Brazilian Real (BRL) is worth 1 US dollar (USD) (January 2019).

Table 3 shows the prices of the products and feedstock considered in the economic analysis. In this study, selling prices of anhydrous ethanol and power are assumed according to the historical average auctions in the Brazilian market (see footnotes).

Table 3 Input parameters of the economic analysis

Parameter	*Value*
Sugarcane (US$/wet tonne)[1,2]	27.26
Sugarcane straw (US$/wet tonne)[3]	18.29
Sugar (US$/kg)[4]	0.48
Electricity (US$/MWh)[5]	60.98

Notes: [1]Average price (December 2018) of sugarcane in São Paulo State (CEPEA, 2020). [2]Tonne of stalks; total reducing sugars content in sugarcane is 15.3%. [3]Values provided by specialists in the sugarcane industry (Watanabe et al., 2020). [4]Average prices (December 2018) of sugar in SP State (CEPEA, 2020). [5]Average price in energy auctions (2018 values) in Brazil (EPE, 2019).

The main costs comprise the capital expense (CAPEX) and operational expense (OPEX), whose calculations are shown in detail in Table 4 (Section 4.2) based on the methodology given in Harrison et al. (2015). It is worthy to remind that the fixed capital cost of the first-generation biorefineries is evaluated in the light of the Brazilian scenario. It must be pointed out that the total plant direct cost (TPDC) represents 70% of the direct fixed capital (DFC) cost, whereas the total plant indirect cost (TPIC) accounts roughly for 17% of the DFC.

The investment cost and the operational costs necessary for maintaining the plant operating are also determined. Regarding the indirect costs, the specialised equipment considers the annual maintenance cost as 3% of the overall DFC, and the local tax fixed at 2% of DFC.

Lastly, it was determined the MSP of ethanol-based on the capital and operating costs. Then, it was compared to the MSP obtained from similar strategies/configurations for ethanol production reported in the literature. To determine the MSP of ethanol, biofuel revenue (BR) from the sales of these biofuel components was determined at the break-even point, in which total revenues and total costs are equal (net present value, NPV = 0). The economic model is based on the production profile obtained in the designed processes. Besides, total revenues include the revenues generated from biofuel and excess electricity sales, whereas total costs include operating costs, ROI, and income tax, assuming a discount rate of 10% (Wang and Tao, 2016).

4 Results and discussion

In this section, the main findings concerning:

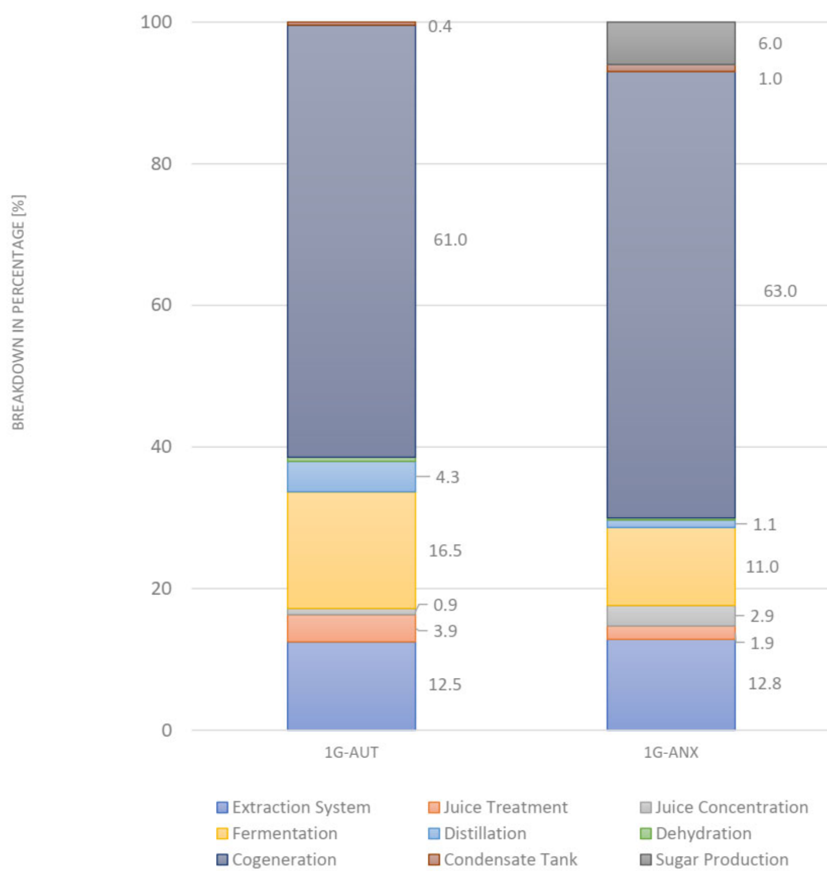
1 the breakdown of exergy destruction

2 the effect on the exergy efficiency of the fraction of straw available in cropland that is fed to the cogeneration system

3 the average unit exergy cost

4 the estimation of the costs for the autonomous and annex sugarcane mills are discussed.

Figure 2 Breakdown of the exergy destruction rate among the various sub-systems of the two types of sugar cane mills (see online version for colours)



4.1 Exergy assessment

As for the irreversibility's of the two types of sugar cane mills, Figure 2 shows the exergy destruction breakdown among each sub-system for the base case (100% of straw consumption). The cogeneration unit exhibits the highest exergy destruction rates, rendering this process the sub-system with the most significant room for improvement. Since the phenomena related to highly irreversible combustion are almost unavoidable in practice, the thermodynamic potential is rather associated with the reduction of losses due to the higher moisture of the biomass fuel when only bagasse is used.

To this end, adequate modifications and revamping procedures, such as the utilisation of the straw, can be implemented to increase the exergy efficiency of the cogeneration system. Furthermore, the fermentation process and the extraction system are responsible for 22%–25% of the exergy destruction. Finally, the consumption of 100% of the straw available in the crops leads to exergy efficiencies of 37.9% and 41.39% for the 1G-AUT and the 1G-ANX plants, respectively.

4.2 Techno-economic analysis

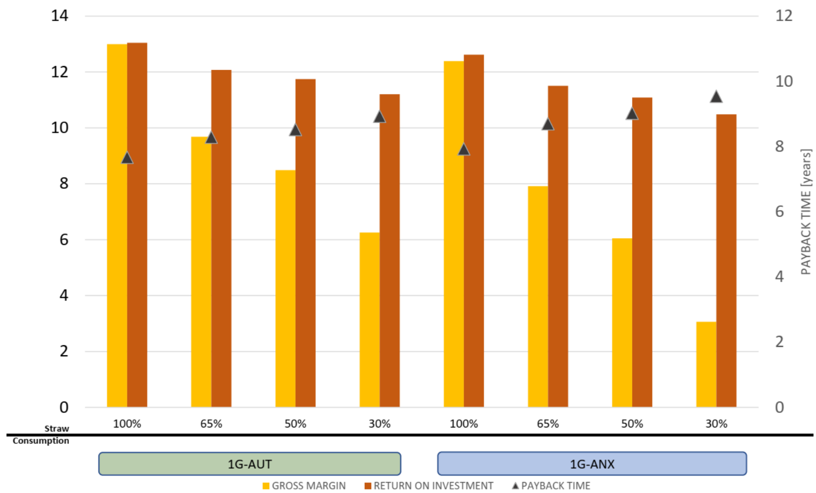
Table 4 summarises some details about the key process indicators (KPIs) calculated by the economic analysis of the reference case (i.e., utilisation of 100% of the straw available in the cropland), such as capital expense (CAPEX) and operational expense (OPEX).

Table 4 Calculated capital cost for the autonomous and annex sugarcane mills

Cost item	*Multiplier factor*		*1G AUT*	*1G ANX*
Total plant direct cost (TPDC)			*(in MUSD)*	
Equipment purchase cost		PC	105	107
Overall installation cost			159	161
Process piping	(0.30 × PC)		31	32
Instrumentation and insulation	(0.20 × PC)		21	21
Electrical	(0.10 × PC)		10	11
Buildings	(0.20 × PC)		21	21
Yard improvement	(0.10 × PC)		10	11
Auxiliary facilities	(0.35 × PC)		37	37
Subtotal	TPDC	394	401	
Total plant indirect cost (TPIC)				
Engineering	(0.10 × TPDC)		39	40
Construction	(0.15 × TPDC)		59	60
Subtotal	TPIC	98	100	
Total plant cost (TPC)	(TPC = TPDC + TPIC)	TPC	493	501
Contractor's fee	(0.05 × TPC)		25	25
Contingency	(0.10 × TPC)		49	50
Direct fixed capital (DFC)	(DFC = TPC + Contractor's fee + Contingency)	DFC	567	576

A profitability analysis of the autonomous and annexed sugarcane mills is carried out considering the fraction of straw consumption (30%–100%). Figure 3 shows the gross margin, the ROI, and the payback time selected as the economic performance indicators for comparing the two sugarcane mill configurations.

Figure 3 Results of the financial analysis for the sugarcane biorefineries as a function of the fraction of cropland straw consumption (see online version for colours)



As it can be seen, the autonomous plant (1G-AUT) offers a slightly better financial performance over the annexed configuration (1G-ANX) regarding the payback period required to recover the initial investment costs. In the former case (1G-AUT), that period is found to be between 7 and 9 years, whereas, for the 1G-ANX configuration, those values ranged between 8 and 10 years, based on the assumptions adopted for the Brazilian sugarcane market. The results of the financial analysis shown in Figure 3 considered the total surplus electricity and ethanol production for each year during the project lifetime (1G-AUT mill). In the case of the 1G-ANX plant, sugar production also has to be considered aside from the electricity generated and the ethanol produced.

Figure 4 shows the breakdown of the production cost, considering the utilities required, the acquisition of the equipment of the biorefinery, labour, and the raw materials consumed. In both configurations (1G-AUT and 1G-ANX sugarcane mills), the raw materials represent the highest contribution to the annual operating cost (OPEX), following by the utility services (e.g., steam, electricity, and water), the equipment, and finally, the labour cost.

The MSP of the products of the biorefineries are summarised in Table 5. It compares the MSP obtained from similar strategies/configurations for ethanol production reported in the literature. These parameters/values are updated to 2019 values.

As a final remark, the potential of CBIOs associated with sugarcane ethanol production and the additional revenues related to the decarbonisation credit market are estimated. To this end, a value of US$10 per CBIO (sold carbon certificates) was adopted, corresponding to a practical value adopted in the sector. In this context, the typical plant (crushing 4 million TC/y) of the sugar and ethanol industry in Brazil could earn $2,679,816 USD/y (1G-ANX) and $2,882,066 USD/y (1G-AUT) of additional revenues via CBIOs, which stands for the saving carbon emissions that otherwise should be paid when using the conventional fuels (e.g., gasoline).

Figure 4 Operating cost breakdown (see online version for colours)

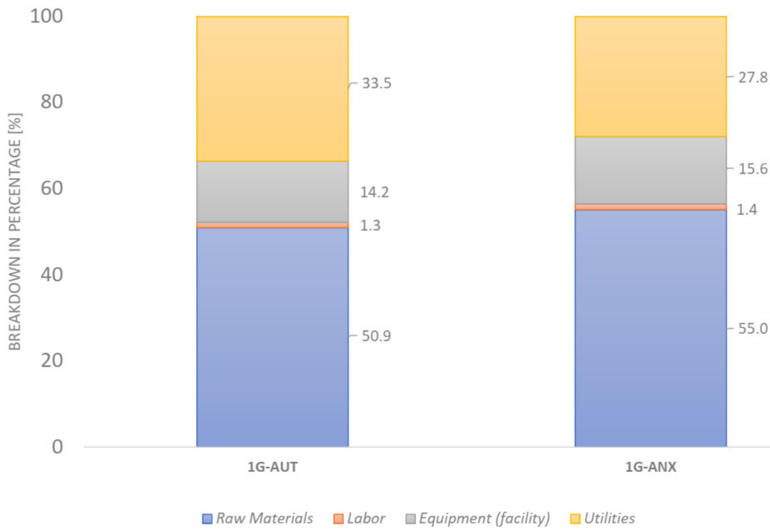


Table 5 Comparison of the ethanol production costs (OP: optimised configuration, MSP: minimum selling prices, SC: sugarcane)

Scenario	*MSP*	*Electricity price*	*Sugarcane price*	*Operational day per year*
	(USD\$/l etOH)	*(USD\$/MWh)*	*(USD\$/TC)*	*(d/y)*
1G–AUT[1]	0.54	76.50	20.91	167
1G–AUT[2]	0.55	73.89	30.80	210
1G–AUT–Op[3]	0.51	60.52	24.52	200
1G–ANX–Op[3]	0.46	60.52	24.52	200
1G–AUT[4]	0.53	60.98	27.26	200
1G–ANX[4]	0.47	60.98	27.26	200

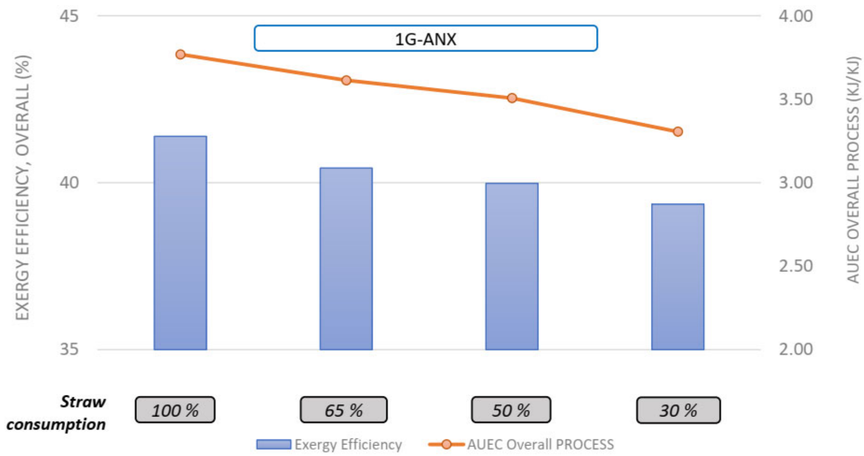
Note: [1]Dias et al. (2011), [2]Furlan et al. (2013), [3]Bonomi et al. (2016), [4]This work.

4.3 Sensitivity analysis to the fraction of straw consumption

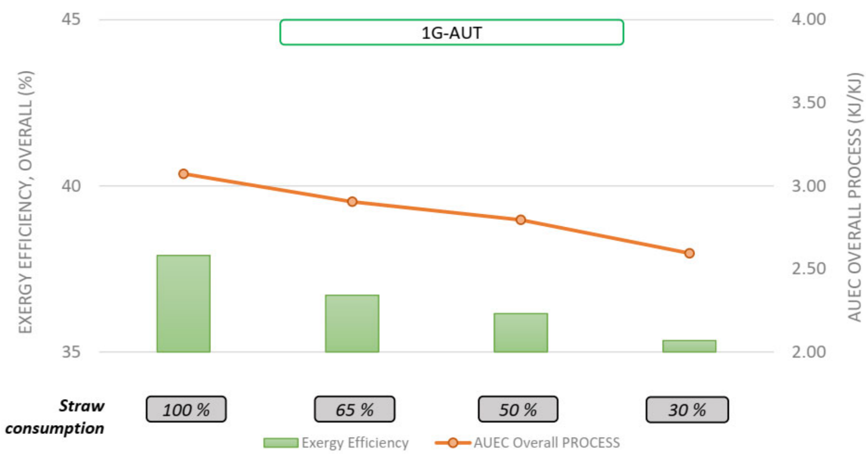
A sensitivity analysis of the effect of the fraction of straw consumed on the performance indicators is performed for both configurations of sugar cane mill (1G-ANX and 1G-AUT). Fractions of 30%, 50%, 65%, and 100% utilisation of the straw material available in the croplands are considered.

Figure 5 shows the AUEC indicator and the exergy efficiency for each system against the fraction of straw utilisation. More specifically, Figures 5(a) and 5(b) show the variation of the AUEC and the exergy efficiency of the overall process (combined sugarcane mill and cogeneration system) for the 1G-ANX and 1G-AUT configurations as a function of the fraction of straw utilised.

Figure 5 Plant-wide exergy efficiencies and average unit exergy costs of the sugarcane mill products as a function of the fraction of sugarcane straw utilised: (a) 1G-ANX biorefinery, (b) 1G-AUT biorefinery (see online version for colours)



(a)

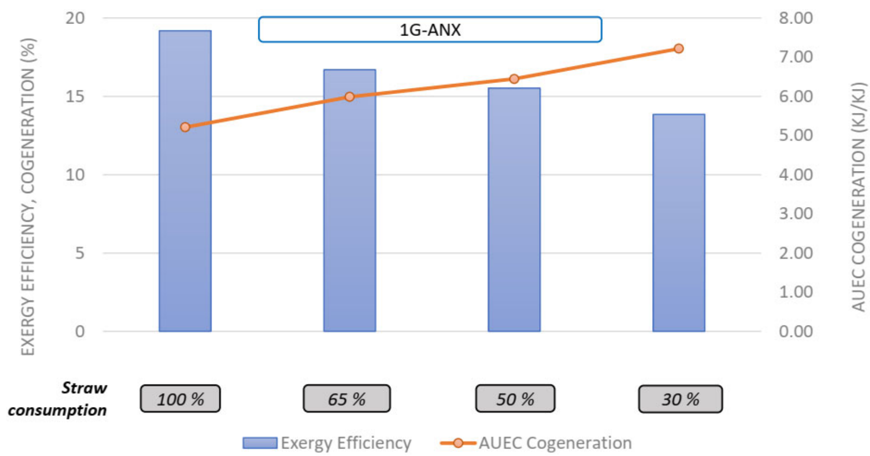


(b)

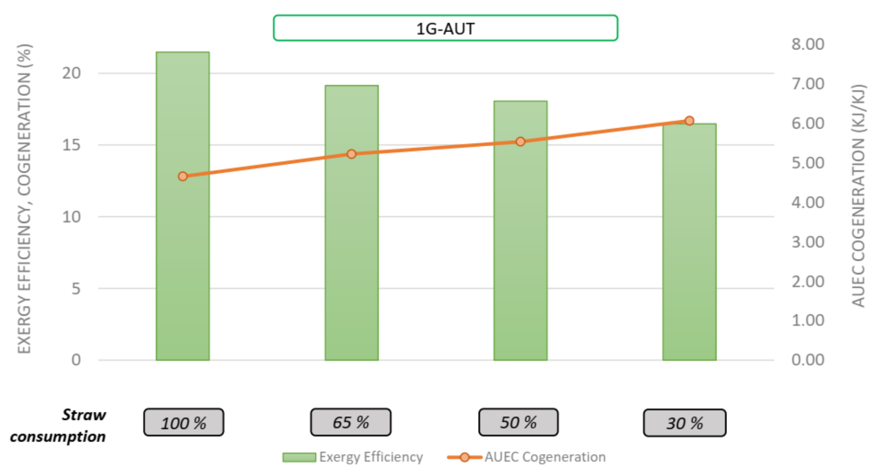
Meanwhile, Figures 6(a) and 6(b) show the variation of the AUEC and the exergy efficiency of both sugarcane mill configurations (1G-ANX and 1G-AUT) focusing only on the cogeneration unit performance. As it can be seen, by increasing the percentage of utilisation of the straw available, the performance of the utility systems also increases. It can be explained by the lower moisture content of the straw, entailing fewer exergy losses associated with the evaporation enthalpy of the water in the exhaust. In this way, higher burning temperatures can be achieved in the boiler.

Accordingly, Figures 5 and 6 show the potential for expanding the electricity generation by recovering the sugarcane straw from the fields. This outcome suits the objective of increasing the contribution of bioelectricity to the Brazilian electric mix, which is expected to thrive under the RenovaBio program (ANP, 2021). This program may support the established environmental targets for the Paris Agreement (37% of GHG emissions by 2025 and 43% by 2030, compared to the 2005 national emissions).

Figure 6 Exergy efficiencies and average unit exergy costs of the products of the cogeneration system as a function of the fraction of sugarcane straw utilised: (a) 1G-ANX biorefinery, (b) 1G-AUT biorefinery (see online version for colours)



(a)



(b)

The potential growth in power generation derived from intensive bagasse and straw utilisation represents a feasible alternative to partially replace natural gas as the primary energy input to thermoelectric plants. This approach could even guarantee the electricity supply during the dry seasons in Brazil, where the lion's share of electricity generation comes from hydroelectric power plants (EPE, 2019; Flórez-Orrego et al., 2014). For instance, it is possible to obtain a lower exergy cost when using all the recovery straw fractions, which represent a competitive AUEC for the overall process reducing these values by 13.5% for the ANX plant and 16.1% in the AUX plant. Similarly, it was found that the use of the straw fraction allows better performance in the cogeneration system achieving a reduction in the AUEC values of 28.6% (ANX) and 25.0% (AUT), respectively. In brief, the export of the surplus electricity derived from the sugarcane cogeneration system into the grid may help to alleviate the shortcomings related to the intermittency of the renewable energy systems, thus pushing forward the diversification of the Brazilian energy mix towards a decarbonisation of the industrial processes and to mitigate energy sector emissions.

5 Conclusions

An exergy and economic assessment of two kinds of first-generation sugarcane biorefineries, autonomous and annexed has been carried out to explore the technological scenarios of sugarcane straw utilisation. This paper discusses the flexibility aspects related to the utilisation of straw available in cropland as a driver for a sustainable ethanol and sugar industry in the Brazilian scenario. As a result, the exergy concept has proven to be a more rational way for proposing performance indicators based on the Second Law of Thermodynamics, capable of comparing and evaluating the performance of sugarcane-based systems when different exergy and mass flow rates, such as bagasse, straw, heat, and power are involved. These aspects show the interaction between the thermodynamic and economic performance of complex multi-generation energy systems. Thus, it was determined the impact of the recovery straw fractions on sugarcane biorefineries and verify the effect in the KPIs proposed in this study focus on the AUEC and the energy efficiency of the plants.

From the techno-economic analysis, it was analysed the operational aspects of the existing technology at the cogeneration plants in sugarcane biorefineries. The potential of the recovery of straw fractions improves the surplus electricity, which represents a significant fraction of the annual revenues. Furthermore, the incomes for an optimised plant of the sugar and ethanol industry receive the increment of profits ($2,679,816 1G-ANX and $2,882,066 1G-AUT, USD/y) resulting from the negotiation of decarbonisation credits (CBios) in the Brazilian sugarcane market based on the carbon emissions saving, which stimulates farmers and biofuel producers to adopt best practices aiming in the whole biofuel production chain and, consequently, bringing benefits for the communities.

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Nomenclature

$\dot{B}$	Exergy flow rate (kW)
b	Specific exergy (kJ/kg)
c	Average unit exergy costs (kJ/kJ)
LHV	Lower heating value (kJ/kg)
W	Power (kW)

Abbreviations

1G-ANX	Annexed plant (first-*generation sugarcane technology*)
1G-AUT	Autonomous distillery (*first-generation sugarcane technology*)
AUEC	Average unit exergy cost
CAPEX	Capital expense
CHP	Cogeneration unit
MUSD	Million US dollars
MSP	Minimum ethanol selling price
letOH	Litres of ethanol
OPEX	Operational expense
ROI	Return on investment
TC	Tons of sugarcane