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Exergy assessment of renewable electricity from sugarcane straw for improved energy integration of sugarcane biorefineries

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Abstract

In 2018, the participation of renewable energy in the Brazilian domestic energy consumption achieved 45.3%, out of which 17.4% corresponds to sugarcane energy, whereas 10.7% is explicitly related to sugarcane bagasse. Sugarcane and straw (*i.e.*, sugarcane tops, dry and green leaves) represent useful energy inputs to the Brazilian electricity mix, often used as supplementary fuels in the cogeneration units of sugarcane biorefineries. However, the collection and conversion of these energy resources are typically performed by using inefficient conversion systems (<30%), which impacts the overall performance of the production process. Hence, this work focuses on existing sugarcane mills and cogeneration systems, aiming to increase the surplus electricity commercialization. Simulation processes are employed to denote incremental modifications related to sugarcane straw recovery utilizing in the harvesting systems. In this context, a technical comparison concerning the exergy efficiency, unit exergy cost, and the irreversibility rate as thermodynamic criteria of these processes is performed to allow identifying potential improvements in the sugarcane mills. A sensitivity analysis is carried out considering the main parameters related to industrial plant scale, operating period, sugarcane straw consumption, and economic criteria to assess different scenarios. Preliminary results show that the techno-economic assessment of straw recovery through harvesting systems increases up to 30% the surplus electricity when it is considered the integration of sugarcane biorefineries with the maximum straw recovery fraction. Also, the increment in the exergy cost of the straw collection influences the extended exergy efficiency of the cogeneration unit and the whole sugarcane biorefinery, rendering this sector a decarbonization alternative for the Brazilian electricity mix.

1 Introduction

In the 2018-2019 sugarcane growing season in Brazil, the ethanol production was based on sugarcane (97.6%) and, to a lesser extent, on corn (2.4%). According to the Brazilian Sugarcane Industry Association, the total production of the former reached around 620 million tons, although the average productivity dropped to 73.50 tons per hectare [1].

Sugarcane represents the main source for electricity generation in the sugar and ethanol industry. One ton of crushed sugarcane generates roughly 250 kg of bagasse and 200 kg of straw and scraps. Thus, not only the amount of electricity demanded by the mills can be covered through these raw materials, but an energy surplus can also be generated and sold to the Brazilian electricity mix. In 2018, the sugar and energy sector added 21.5 thousand GWh of electricity to the Brazilian Interconnected System [2].

In Brazil, projections for the next ten years in the sugarcane supply chain point to higher growth in terms of ethanol biofuel production and surplus electricity generation, compared to the past decade, which is leveraged by the RenovaBio program, a stimulating policy for increasing the energy efficiency and reducing the CO_2 emissions in the sugar and ethanol production sector[3].

From this perspective, this work focuses on the retrofit of existing sugarcane mills cogeneration systems, aiming to increase the surplus electricity commercialization, considering straw recovery and its operation in the season/off-season periods. Furthermore, a performance comparison between an autonomous (1G-AUT) and an annexed (1G-ANX) distilleries are carried out regarding: *(i)* the global exergy efficiency, *(ii)* the average unit exergy cost, and *(iii)* the exergy destruction rate as thermodynamic criteria to allow identifying potential improvements in the Brazilian biorefinery scenario.

2 Material and methods

In this section, the different scenarios analyzed and the thermodynamic and economic methodologies, used to assess and compare their performance, are discussed.

2.1 Description of the technological scenarios

In the technological scenarios, the first-generation ethanol production processes were considered bearing in mind data for an autonomous distillery (1G-AUT) and an annexed plant (1G-ANX) with a milling capacity of 4 million tons of sugarcane (TC) in 200 days per year, and recovering sugarcane straw produced in the field. Firstly, sugarcane undergoes to the cleaning and crushing steps. Hereafter, 125 kg of bagasse (dry basis) are produced per TC. The lower heating value (LHV) of bagasse with 50 wt.% moisture content is 7.5 MJ/kg. Furthermore, a certain amount of the sugarcane straw (*i.e.* tops and leaves) is transported to the cogeneration plant, about 140 kg straw/TC (dry basis). The LHV of straw with 30 wt.% moisture content is 11.5 MJ/kg.

General simulations of both 1G-AUT and 1G-ANX models were developed based on key parameters reported for conventional/standard mills [4–6]. The processes involved in the sugarcane distillery and the annexed plant were separated into representative control volumes, as illustrated in Fig. 1. In this figure, the lignocellulosic materials (e.g., bagasse and straw) are sent to the cogeneration unit (CHP), which converts these materials into heat and electricity. A steam cycle with backpressure steam turbines (boiler parameters: 65 bar, and 480°C) is adopted to model the CHP unit. It must be underlined that straw consumptions of 30%, 50%, 65%, and 100% of the available lignocellulosic material in sugarcane fields are considered as input to the CHP unit for each system. The values of the main operating parameters for each process are specified in Silva Ortiz et al. [7] for standard sugarcane mills in Brazil.

From the agricultural system perspective, a key factor associated with 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 energy enterprise. In this work, to quantify this effect, a typical distance of 50 km was adopted [8]. More details of the agricultural and industrial aspects involved in the electricity production from sugarcane straw can be found elsewhere [8,9].

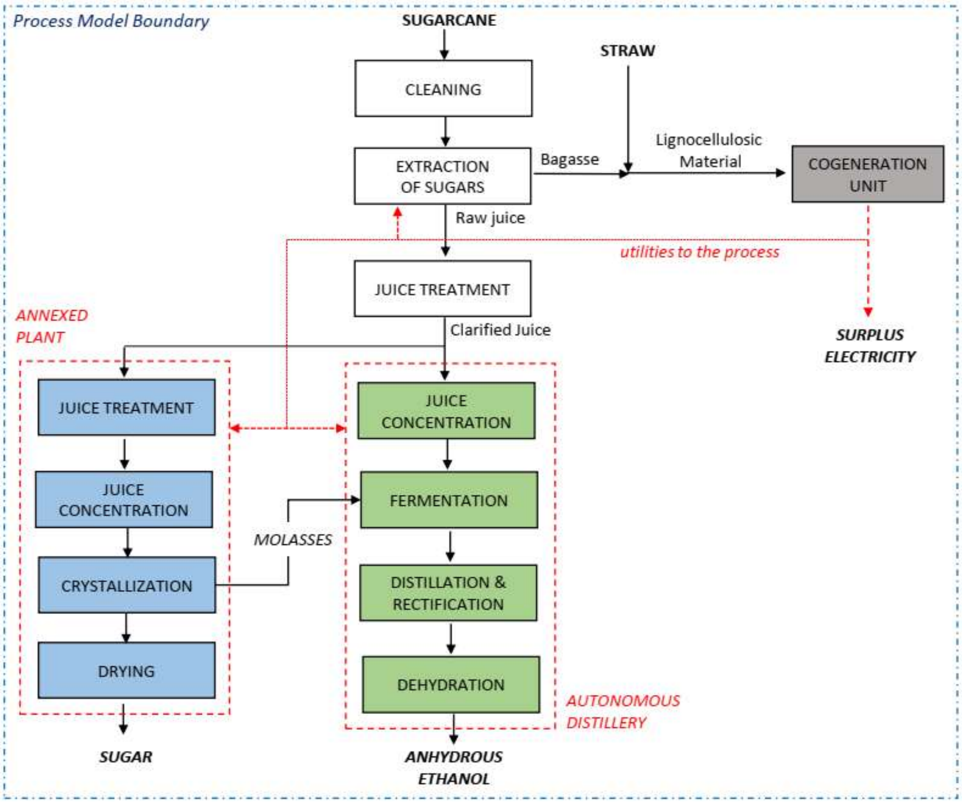

Figure 1: Main processing operations of the first generation annexed and autonomous sugarcane biorefineries

2.2 Exergy analysis

Exergy concept is defined as the capability to do work using thermodynamically perfect processes, which account for both the quantity (1st Law) and quality (2nd Law) of a particular conversion energy process. Thus, exergy analysis reflects the different thermodynamic values of the energy forms and quantities based on the Second Law of Thermodynamics [10]. In this work, the total exergy of a material stream or a system is defined as:

$$B_{tot} = B_{ch} + B_{ph} \tag{1}$$

B_{ch} This term presents the chemical exergy, (kW).
B_{ph} This term presents the physical exergy, (kW).

As for the case of sugarcane biomass, the term B_{ph} is oftentimes neglected since biomass generally enters at the ambient conditions of pressure and temperature, whereas the term B_{ch} is defined as specified in Eq.(2):

$$B_{biomass} = \dot{m}_{biomass} \beta \, LHV_{biomass} \tag{2}$$

where the mass flow rate *(m)* is expressed in *kg/h*, the lower heating value *(LHV)* of biomass is given in *kJ/kg*; and $\boldsymbol{\beta}$ is the ratio between the chemical exergy to the LHV, which can be calculated from correlations reported for wood with an O/C ratio ≤ 2 [11], according to Eq.(3):

$$\boldsymbol{\beta} = \frac{1.044 + 0.0160\left(\frac{H}{C}\right) - 0.3493\left(\frac{O}{C}\right) * \left(1 + 0.0531\left(\frac{H}{C}\right)\right) + 0.0493\left(\frac{N}{C}\right)}{1 - 0.4124\left(\frac{O}{C}\right)} \tag{3}$$

where the mass fractions of carbon, hydrogen, oxygen, and nitrogen (C, H, O, and N) are known from the ultimate analysis of the biomass.

On the other hand, the irreversibility rate associated with the rate of exergy destruction allows working out a thorough diagnostic of the actual system performance in terms of the deviation from the ideal standard. The minimization of the exergy destruction can also be used as a rational target for optimization purposes. The exergy balance can be adopted to compute the plantwide and component-wise irreversibility distribution. In a steady-state operating condition, the exergy balance of a system can be written in Eq.(4).

$$\sum B_{in} = \sum B_{out} + B_{destroyed} \tag{4}$$

$\sum B_{in}$	This term presents the exergy inputs of the system (kW).
$\sum B_{out}$	This term presents the exergy outputs of the system (kW).
$B_{dest.}$	This term presents the exergy destruction rate due to the actual processes (kW).

Lastly, the average unit exergy cost (AUEC) is adopted as a metric for the cumulative irreversibility and exergy consumption along with the energy conversion processes. Thus, a higher irreversibility rate translates into higher unit exergy costs. It must be noted that the exergy cost indicator brings about a closer insight into the contribution of each product to the overall plant efficiency based on the Second Law of Thermodynamic [12]. According to Eq. (5), the average unit exergy cost c (kJ/kJ) of the combined anhydrous ethanol production and the electricity generated can be determined as the weighted average of the exergy cost of the ethanol unit and the power generation system:

$$AUEC_{process} = \frac{c_{ethanol} * B_{ethanol} + c_{electricity} * B_{electricity}}{B_{ethanol} + B_{electricity}} \tag{5}$$

2.3 Techno-economic analysis

A discounted cash flow analysis is applied in order to estimate the gross margin, the return on investment (ROI), and the payback time of the biorefinery scenarios in the Brazilian context, using the following assumptions: *(i)* building and start-up in 2 years, *(ii)* project lifetime of 20 years with an operating factor of 200 days/y, *(iii)* no subsidies on capital investment costs, *(iv)* the nominal capacity of 100% during the first year of operation, *(v)* no debt and 100% equity, *(vi)* 34% tax rate, *(vii)* 10-year linear depreciation and working capital as 2% of capital investment, and (*viii*) the exchange rate (January 2019) was R$ 3.79 (BRL) per U.S. dollar (USD).

Table 1 summarizes the input parameters considered in the economic analysis. In this study, selling prices of anhydrous ethanol and power are assumed, taking into account the historical average auctions from the Brazil market.

Table 1: Input parameters of the economic analysis

Parameter	Value
Sugarcane (US$/wet tonne)[1,2]	27.26
Sugarcane straw (US$/wet tonne)[3]	18.29
Anhydrous ethanol (US$/L)[4]	0.66
Sugar (US$/kg)[5]	0.48
Power or Electricity (US$/MWh)[6]	60.98

[1] Average prices (December 2018 values) from sugarcane in São Paulo-SP State (CEPEA, [13]).

[2] Tonne of stalk; total reducing sugars content in sugarcane is 15.3%.

[3] Values provided by specialists in the sugarcane industry [8].

[4] Anhydrous ethanol prices paid to the producer in the period from 2016 to 2019 (CEPEA, [13]).

[5] Average prices (December 2018 values) of sugar in SP State (CEPEA, [13]).

[6] Average price in energy auctions (2018 values) in Brazil (EPE, [14]).

The main parameters comprise in the capital expense (CAPEX), and operational expense (OPEX) estimation are exemplified in Table 2 and Fig. 3 based on the assumptions given in [15].

3 Results and discussion

3.1 Exergy assessment

As for the irreversibilities pertaining to the biorefineries, Fig. 2 shows the exergy destruction breakdown for each sub-system. It is important to notice that the cogeneration unit shows the highest exergy destruction rates, rendering this process the sub-system with the largest room for improvement by implementing the adequate modifications and revamping processes in order to increase the exergy efficiency. In this work, the operating parameters of the live steam produced in the boiler are set as 65 bar and 480°C.

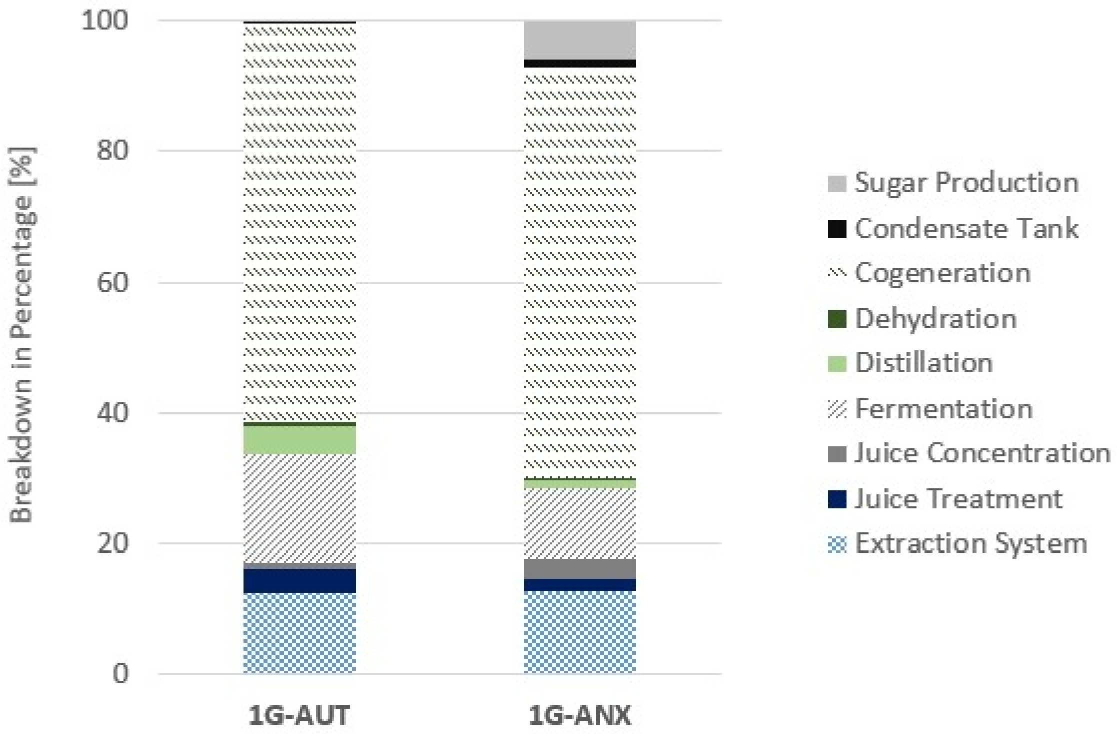

Figure 2: Breakdown in the percentage of the exergy destruction rate for each type of sugar cane biorefinery

As it concerns the overall exergy efficiency of these two bioenergy technological configurations (base case: straw consumption of 100%), in the 1G-AUT system, that value achieved 37.9%, whereas, in the case of the 1G-ANX plant, the overall exergy efficiency reached 41.39%.

3.2 Sensitivity analysis

A sensitivity analysis of straw consumption was performed for the ethanol configurations. Thus, it was adopted in the models 30%, 50%, 65%, and 100% of the straw material available in the croplands. Figure 3 displays the AUEC indicator against the exergy efficiency for each system. Firstly, Fig. 3a (1G-ANX) and Fig. 3c (1G-AUT) shows the variation of the AUEC and the exergy efficiency of the overall process in terms of the percentage straw participation.

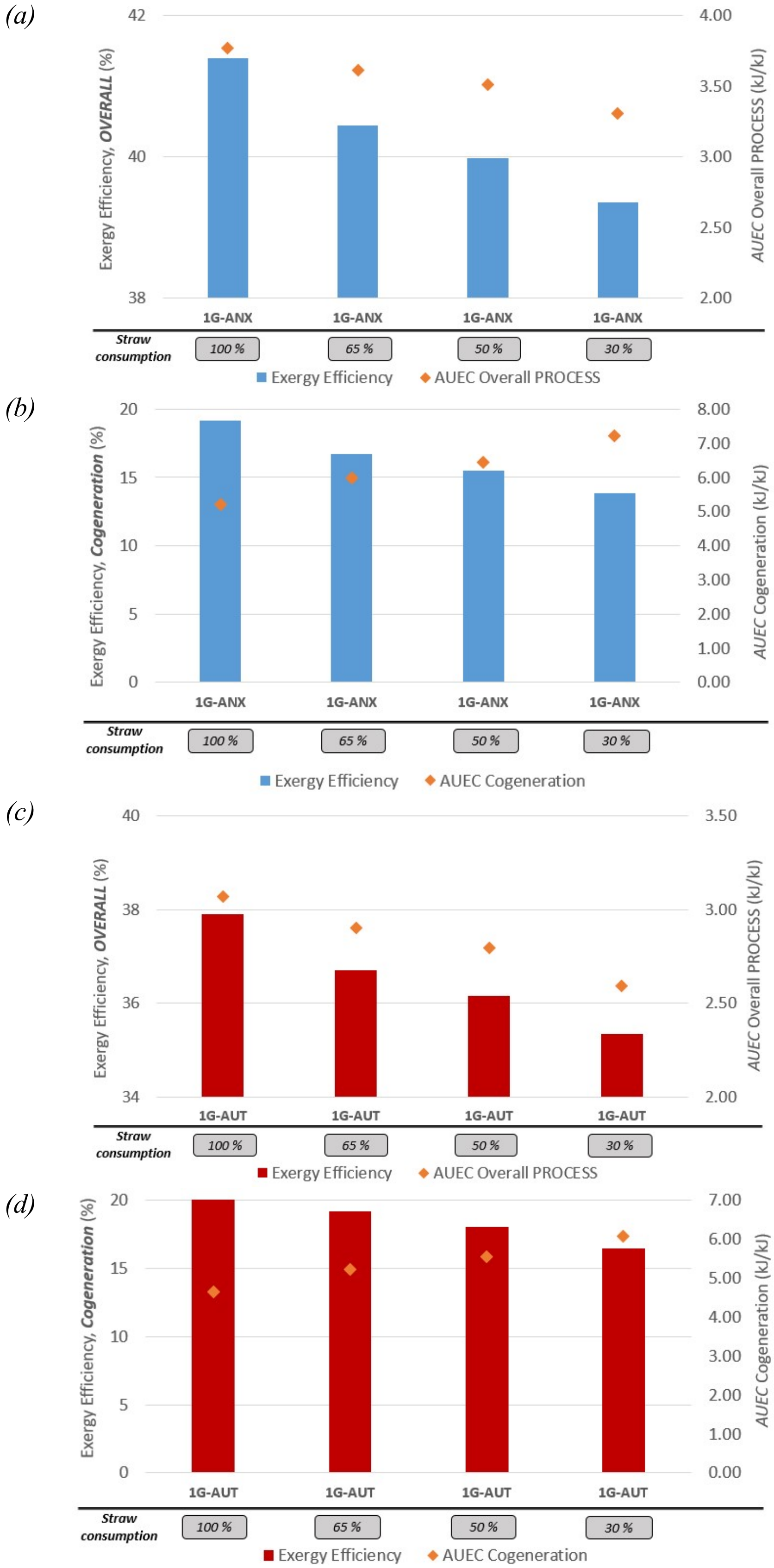

Figure 3: Effect of the percentage of straw in cropland fed to the cogeneration system on the exergy efficiency and the average unit exergy cost

Fig. 3b (1G-ANX) and Fig. 3d (1G-AUT) displays the variation of the AUEC, and the exergy efficiency focus on the cogeneration unit to show that this increases with the percentage straw participation. For instance, it was noted that more straw there represents less water in the feedstock (fuel), and the less water since less evaporation of the water occurred and the higher the adiabatic flame temperature of the furnace is achieved.

On the other hand, a profitability analysis of the autonomous and annexed plants is carried out considering the amount of straw consumption. The gross margin, the return on investment (ROI), and the payback time are selected as economic performance indicators (see Fig. 4).

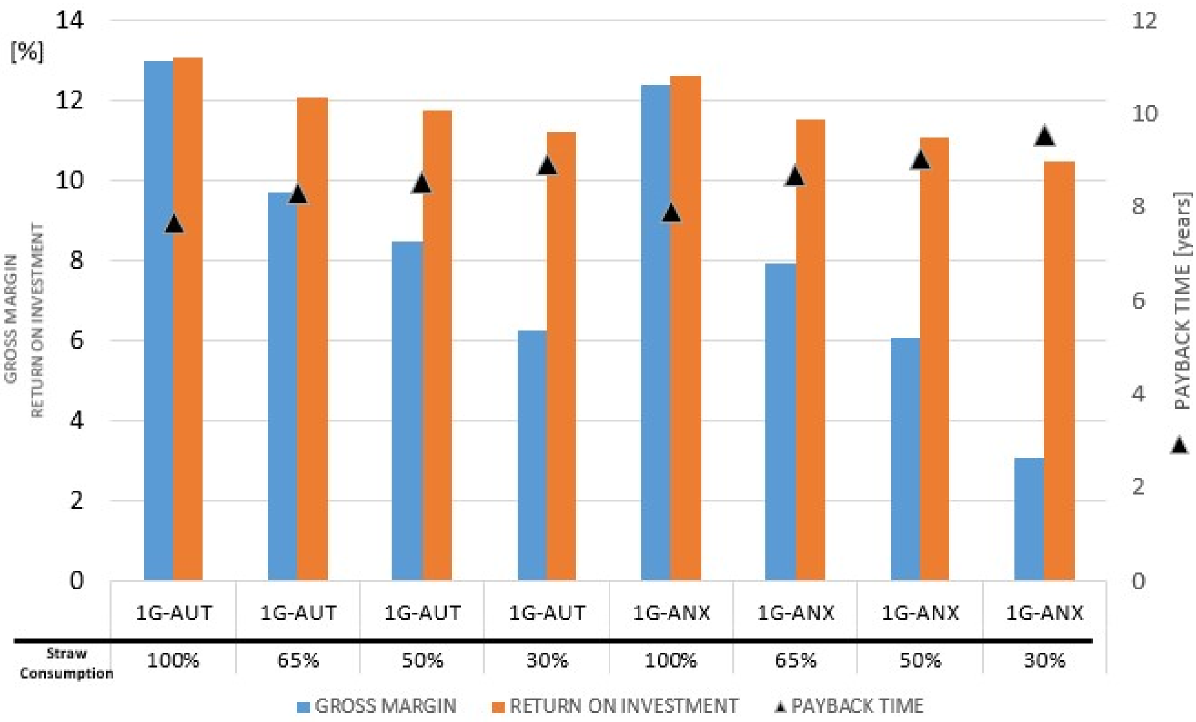

Figure 4: Financial analysis results for the sugarcane biorefineries as a function of the percentage of cropland straw consumption

In terms of the economic indicators, the autonomous plant (1G-AUT) offers a slight advantage over the annexed configuration (1G-ANX) regarding the payback period required to recover the investment costs. In the former case, that period was found to be between 7 and 9 years, whereas for the and 1G-ANX configuration, those values ranged between 8 and 10 years, based on the assumptions adopted for the Brazilian sugarcane market (Tab. 1).

In addition, the results of the financial analysis shown in Fig. 4, the total electricity and ethanol production for each year during the project lifetime of the 1G-AUT are considered. Meanwhile, in the case of the 1G-ANX plant, sugar production has to be also considered aside from the electricity generated and the ethanol produced. In both systems, the investment cost and the operational costs, necessary for maintaining the plant operative are determined. The details of the key process indicators used in the financial analysis of the base case (*i.e.,* 100% of the straw available), such as capital expense (CAPEX) and operational expense (OPEX) are summarized in Table 2. It is worthy to notice that the Fixed Capital Cost of the first generation biorefineries is evaluated in light of the Brazilian context. It must be pointed out that the Total Plant Direct Cost (TPDC) represents 70% of the Direct Fixed Capital Cost (DFC), whereas the Total Plant Indirect Cost (TPIC) accounts for roughly 17% of the DFC.

Table 2: Fixed capital cost estimation for the autonomous and annex sugarcane distilleries studied in the Brazilian context (in MUSD)

Cost item	***Multiplier factor***		***1G AUT***	***1G ANX***
TOTAL PLANT DIRECT COST (TPDC)				
Equipment Purchase Cost		PC	105	107
Overall Installation Cost			159	161
Process Piping	(0.30 x PC)		31	32
Instrumentation and Insulation	(0.20 x PC)		21	21
Electrical	(0.10 x PC)		10	11
Buildings	(0.20 x PC)		21	21
Yard Improvement	(0.10 x PC)		10	11
Auxiliary Facilities	(0.35 x PC)		37	37
	Subtotal	**TPDC**	**394**	**401**
TOTAL PLANT INDIRECT COST (TPIC)				
Engineering	(0.10 x TPDC)		39	40
Construction	(0.15 x TPDC)		59	60
	Subtotal	**TPIC**	**98**	**100**
TOTAL PLANT COST (TPC)	(TPC = TPDC + TPIC)	TPC	493	501
Contractor's fee	(0.05 x TPC)		25	25
Contingency	(0.10 x TPC)		49	50
DIRECT FIXED CAPITAL (DFC)	(DFC = TPC + Contractor's fee + Contingency)	**DFC**	**567**	**576**

Figure 5 shows the economic cost breakdown considering the required utilities, the purchase of the refinery operation units, the labor, and the raw materials consumed. In both configurations, the raw materials represent the highest contribution of the annual operating cost (OPEX estimation), following by the utility services (*e.g.,* steam, electricity, and water), the equipment, and finally, the labor cost in a lesser extent. Regarding the indirect costs, the specialized equipment considers the annual maintenance cost as 3% of the overall direct fixed capital (DFC), and the local tax fixed at 2% of DFC.

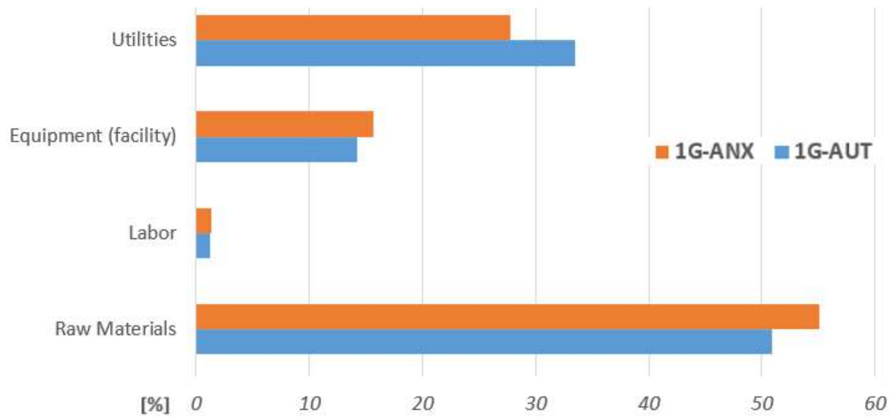

Figure 5: Operating cost distribution

4 Conclusions

An exergy and economic assessment of two kinds of first-generation sugarcane biorefineries, namely an autonomous (only ethanol) and an annexed (sugar and ethanol combined production), has been carried out to explore the technological scenarios of sugar cane straw utilization. This paper discusses the results for the global efficiency and economic profitability in the context of the Brazilian scenario. As a result, the exergy could be interpreted as a more rational indicator, based on the Second Law of Thermodynamics, capable of comparing and evaluating the performance of sugarcane-based systems when both heat and power exergy flows are involved. These results may show the potential synergies between the thermodynamic and economic performance of complex multi-generation energy systems.

The surplus electricity represents a significant fraction of the annual revenues for those bioenergy conversion systems. This fact is a consequence of the operational season/off-season periods, logistic aspects (mainly transport and straw recovery), and the existing technology at the cogeneration plants in sugarcane biorefineries. Thus, 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 decarbonization of the industrial processes.

Nomenclature

1G-ANX	Annexed plant (first-generation sugar cane technology)
1G-AUT	Autonomous distillery (first-generation sugar cane technology)
AUEC	Average unit exergy costs (kJ/kJ)
CAPEX	Capital expense (MUSD)
CHP	Cogeneration unit
LHV	Lower heating value (kJ/kg)
MUSD	Million United States Dollars
OPEX	Operational expense
ROI	Return on investment (%)
TC	Tons of sugarcane

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