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Optimal modes of operation and product cost allocation in sugarcane steam cogeneration plants

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ABSTRACT

Sugar and ethanol production from sugar cane is one of the most competitive sectors of Brazil's economy. The bagasse generated during the production process is used as fuel in cogeneration plants that provide thermal and electrical energy to the process. In the last decades, many sugar cane factories have produced a surplus of electricity that may be sold to the grid as a new product. This paper applies energy billing optimization and thermoeconomic analysis to a sugarcane steam cogeneration plant to determine the optimal operating mode of the plant, unveils the cost formation process of its internal products (refinery heat, process heat, and consumed electricity), and examines how the results are affected by: (i) the demand for the plant's energy services, (ii) the availability of bagasse, and (iii) the selling price of surplus electricity. The thermoeconomic analysis involves a detailed study of the cost formation process, which is achieved through the decomposition of the steam cycle of the cogeneration plant into subcycles. Three main subcycles, in addition to the deaeration cycle and other auxiliary subcycles, have been identified: the cogeneration cycle generating work in the high-pressure turbine and refinery heat (subcycle one), the cogeneration cycle generating work in the high- and medium-pressure turbines and process heat (subcycle two), and the condensing cycle that generates only work in the high-, medium-, and low-pressure turbines (subcycle three). These subcycles make up the productive structure of the steam cogeneration plant and explain how water/steam goes through energy conversion processes from the bagasse energy to the heat and electricity produced. Both the optimization model and the thermoeconomic analysis serve as valuable tools for planning in response to potential changes in bagasse and electricity market prices, as well as fluctuating product demand conditions. In the base case, combining optimization with thermo-economic analysis, the unit monetary cost of the final products has been determined: heat for refinery (8.85 R$/MWh), electricity sold (183.60 R$/MWh), internally consumed electricity (41.51 R$/MWh), and process heat (8.85 R$/MWh).

Nomenclature		Units
b	Specific exergy	kJ/kg
B	Exergy value of the flow	MW
B*	Exergetic cost	MW
BIG	Biomass integrated gasifier	-
C	Exergoeconomic costs	R$/h
c	Unit exergoeconomic costs	R$/MWh
CEST	Condensing extraction steam turbine	-
CHP	Combined Heat and Power	-
CLC	Collector	-
CND	Condenser	-
d	Discount	-

(continued on next column)

(*continued*)

Nomenclature		Units
DEA	Deaerator	-
E	Electrical power	kW
F	Bagasse consumption	kW
GTCC	Gas turbine combined cycle	-
HT	High-pressure turbine	-
k*	Unit exergetic cost	kJ/kJ
LHV	Lower heating value	kJ/kg
LT	Low-pressure turbine	-
Min	Minimizing	-
MT	Medium-pressure turbine	-

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(*continued*)

Nomenclature		Units
ORC	Organic Rankine cycle	-
P	Pressure	bar
p	Price	R$/kWh
PMP	Pumps	-
Q	Heat demand	kW
T	Temperature	°C
VLV	Valve	-
x	Unit exergoeconomic cost with discount	kJ/kJ
$\dot{m}$	Mass flow rate	kg/s
Greek symbols		
Δ	Variation	-
η	Efficiency	%
λ	Marginal costs	R$/kWh
Subscripts and superscripts		
0	Environment	-
bag	Bagasse	-
conE	Condenser (Energy base)	-
d	Demand	-
ele	Electricity	-
in	Inlet	-
j	Flow	-
ope	Operation	-
out	Outlet	-
PMP	Pump	-
proB	Process (Exergy base)	-
proE	Process (Energy base)	-
Q	Heat demand	-
refB	Refinery (Exergy base)	-
refE	Refinery (Energy base)	-
v	Sold	-

1. Introduction

Traditionally, sugar mills produce their electricity with cogeneration to meet on-site needs by burning bagasse or other residual fuels. However, only in recent decades and in some countries have there been incentives for efficient cogeneration due to the unavailability of tariffs for the sale of excess electricity produced to the grid. Introducing such tariffs has prompted the technological improvement of the classic Rankine steam cycles and the proposal to use new cycles.

A vital characteristic of the Brazilian Energy Matrix [1] is the significant presence of Renewables, whose participation reached 48.4 % in 2020, corresponding 19.1 % to sugarcane biomass, 12.6 % to hydropower, 8.9 % to wood and charcoal, and 7.7 % to other renewables. Concerning the electricity matrix, the share of Renewables reached 84.8 %, corresponding 65.2 % to hydropower, 9.1 % to biomass, 8.6 % to wind, 1.7 % to solar PV, and 0.2 % to other renewables. The sugarcane industry produces sugar, ethanol, and electricity as primary products, and considering the data mentioned above, it can be stated that it has a strong presence as a primary energy source. Another aspect of this industry is that it is energy self-sufficient. That being so, the energy used in the production process is also produced (from bagasse) in the same process. The sugarcane industry is significant for the country, and given that it is also an energy industry, there is no doubt that energy management holds importance in its industrial process [2]. Still, two technologies have emerged that use sugarcane bagasse as a feedstock: bioelectricity generation and second-generation ethanol. As a result, a new discussion has arisen for the future configuration of the sugarcane industry: should bagasse be used to generate bioelectricity or produce second-generation ethanol? [3].

Thermodynamics and economic analysis began to be applied to reduce steam and electricity consumption in the plants, thus increasing the surplus electricity available for sale. Ensinas et al. [4] revealed that modern sugar mills equipped with advanced technology can produce considerable electric power for the central grid. They analyzed steam demand reductions on sugar cane plants and alternatives for the cogeneration systems, aiming at increasing surplus electricity generation. Bocci et al. [5] explored the potential performance of improvements in higher temperature and pressure Rankine cycles and innovative combined cycles based on gasifier plus hot gas conditioning and gas turbine or molten carbonate fuel cells. More recently, Pedroso et al. [6] conducted a technical analysis of introducing Biomass Integrated Gasifier/Gas Turbine Combined Cycle BIG/GTCC technology in the sugarcane industry for electricity and heat generation, using wet sugarcane bagasse as fuel. All agree that the BIG/GTCC systems can produce more electricity per unit of biomass consumed than the conventional Condensing Extraction Steam Turbine (CEST) systems.

The efficient conversion of sugarcane, the world's largest crop, into energy carriers, namely second-generation ethanol, and electricity, offers a renewable strategy to meet future energy needs but requires a continuous scientific, technical, and economic effort. This conversion uses complex processes with numerous unit operations. These processes require the application of systematic simulation, thermal integration, and optimization methodologies, as well as detailed technical and economic evaluation [7]. The consolidation of second-generation ethanol will provide a more significant amount of ethanol without increasing sugarcane acreage.

Process integration techniques and thermoeconomic analysis have started to be applied recently in the last decades for biofuel production [8]. The term thermoeconomics corresponds to the combination of thermodynamic and economic analyses [9,10]. Thermoeconomics determines the cost formation process of the internal flows and final products of energy systems and process plants. Additionally, studies [11,12] contribute valuable insights into thermoeconomic analysis in this context. In this way, achieving a better assessment of the different production alternatives and a more accurate understanding of the internal economic processes in the production process as a whole is possible. Ensinas et al. [13] performed a thermoeconomic optimization of a sugarcane mill's evaporation system and heater network design. Palacios-Bereche et al. [14] assessed the exergy analysis and exergy cost associated with the ethanol production process from sugarcane biomass, including the route of bagasse enzymatic hydrolysis. The combined sugar and ethanol production process from sugar cane is a paradigmatic application for energy integration strategies because of the high number of hot and cold streams involved, the external hot utility requirement at two temperature levels for juice evaporation and crystallization, and the electricity demand for juice extraction by milling. These conditions make it convenient to combine the sugarcane process with a CHP system fuelled by bagasse, the main by-product of juice extraction [15]. Pina et al. [16] accomplished a joint assessment to evaluate the reduction of process steam demand and water usage obtained through heat integration and exergy analysis to quantify the reduction in irreversibility generation owing to the heat integration procedure. The results showed that heat integration promoted a reduced steam consumption of around 35 % (with a decrease in water collecting requirement) compared to conventional plants without heat integration.

Determining the productive structure is crucial in thermoeconomic analysis [12]. Depending on the type of analysis, different levels of accuracy of the results are necessary, which means that each thermoeconomic analysis requires a specific level of disaggregation of components and flows. The deeper and more detailed the disaggregation is, the more precise the interpretation of the obtained costs will be and the more comprehensive the catalog of applications to theoretical and practical problems. Detailed and accurate results in thermoeconomics can be obtained with the disaggregation of the thermal energy conversion systems into subsystems. It is worth noting that some thermoeconomic studies have focused on proposals that use the disaggregation of physical exergy flow instead of the approach presented in this work that disaggregates the system into subcycles [12,17]. Thus, Lozano and Valero [18] have applied the disaggregation of exergy gas flow-streams into their thermal and mechanical exergy components in the thermoeconomic analysis of gas turbine cogeneration systems; Santos et al. [19] proposed the disaggregation of physical exergy into Helmholtz energy and flow work in steam power cycles; and Faria et al. [20] compare different disaggregation of exergy flows in order to allocate greenhouse gas emissions to the final products of a gas turbine cogeneration system. Thermoeconomic analysis, performed in this research, involves a detailed study of the cost formation process, which is achieved through the decomposition of the steam cycle of a sugarcane cogeneration plant into subcycles. Three main subcycles, in addition to the deaeration cycle and other auxiliary subcycles, have been identified: 1) cogeneration cycle generating work in the high-pressure turbine and refinery heat, 2) cogeneration cycle generating work in the high- and medium-pressure turbines and process heat, and 3) condensing cycle that generates only work in the high-, medium-, and low-pressure turbines. These subcycles represent the productive structure of the steam cogeneration plant and explain how water/steam goes through energy conversion processes from the bagasse energy to the heat and electricity produced.

Just as it is possible to decompose the basic configuration of a generic energy conversion system into elementary thermodynamic cycles, it is possible to use the reverse approach to synthesize the basic configuration of a candidate optimal system artificially according to the procedure that is outlined by Toffolo [21], which was later extended and generalized, giving rise to the SYNTHSEP methodology for the synthesis and design of energy systems. According to Lazzaretto et al. [22], the basic configuration of a generic energy conversion system can be ultimately decomposed into a set of elementary thermodynamic cycles. They proposed a bottom-up methodology, which relies on the idea that the system configuration is undoubtedly based on one or more thermodynamic cycles that may share some processes or be combined in a cascade form. This original synthesis/design optimization methodology and its effectiveness in the search for the best configuration have been demonstrated in different systems: bottoming steam cycle of the CHP plant that supplies heat and electric power to a combined sugar and ethanol production process [21], two-pressure level ORC system configuration [22], and supercritical CO_2 cycles in waste heat recovery applications [23].

The combination of thermoeconomic analysis and mathematical optimization offers a dual perspective on improving energy processes and helps answer concrete questions related to energy management [24,25]. The optimization of the operation allows to establish the operating status of the cogeneration plant that leads to the best economic result. It also provides marginal costs to assess resource availability (bagasse) and internal product demand (steam at different pressure levels and electricity consumption). The thermoeconomic analysis allows to identify which production subcycles have been activated to reach the optimal operating state, and from this knowledge to recognize the transformation processes involved in obtaining the different products and their costs. These findings improve the understanding of the economic dynamics of the plant and are useful for decision making. Finally, the consideration of the income from the sale of electricity as a credit to the production allows to estimate an appropriate discount to the products consumed internally in the industry served by the cogeneration plant.

In summary, the novelty of integrating thermoeconomic analysis with optimization techniques, the focus on the sugarcane industry, the detailed subcycle analysis, and the practical implications for energy management collectively underline the significance of the present work in advancing knowledge and practices within the field of energy production and optimization.

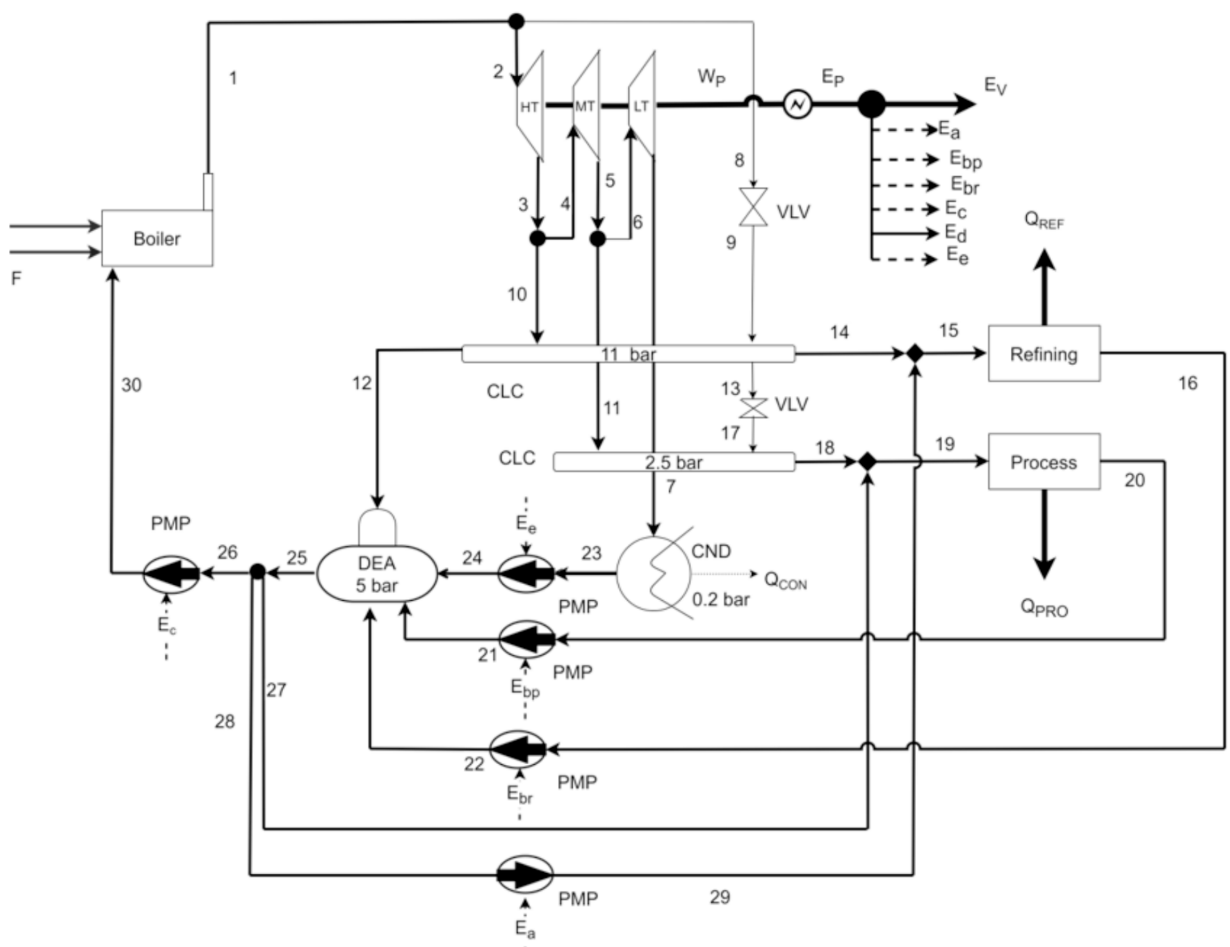

Fig. 1. Physical structure of the cogeneration system.

2. Cogeneration plant

The cogeneration system studied in this work is based on the Colombo S.A Sugar and Alcohol Plant [26,27] in São Paulo, Brazil, and is presented in Fig. 1. The cogeneration system is composed of a boiler, a high-pressure turbine (HT), a medium-pressure turbine (MT), and a low-pressure turbine (LT), two valves (VLV) in case it is necessary to bypass the flow of the turbines, two collectors (CLC), a condenser (CND), a deaerator (DEA), five pumps (PMP), two heat consumers (Refinery, Process), and an alternator.

It is essential to highlight that, in the physical structures presented in this section, as illustrated in Fig. 1, one can observe the presence of bold and thinner lines. The bold lines are associated with a mass flow, whereas the lighter lines are not. Thus, there is no flow through the lighter lines during operation, suggesting that the equipment connected to these lines is not operational. This outcome is a result of optimization, as can be observed in Section 3.

This work focuses on the plant utility system, where the input is sugarcane bagasse resulting from the milling process in the plant, and the final products are net electricity, heat demand for the process (sugar production), and refinery (alcohol production). The plant has a milling capacity of approximately 1000 tons of sugarcane per hour, generating 280 tons of sugarcane bagasse per hour (the energy input for this system) with a lower heating value (LHV) of 7500 kJ/kg and specific exergy (b) estimated by the Szargut et al. method [10] of 9941 kJ/kg.

In the base case, the heat demands required for the process (Q_{proE}) and refinery (Q_{refE}) are fixed at 32,800 and 23,000 kW, respectively.

In addition to the electrical power consumption of the pumps (E_a, E_{bp}, E_{br}, E_c, E_e), there is an internal electrical demand (E_d) of 30,000 kW required to operate the sugar cane mills and other equipment.

Certain assumptions have been made, including the assumption that the processes are in a steady state. In Table 1, various system parameters are shown. It should be noted that the turbines exhibit the same isentropic efficiency. Also, the five pumps have the same isentropic efficiency. Additionally, it is assumed that there is a saturated vapor at states 15 and 19 and a saturated liquid at states 23 and 25. There are no changes in kinetic and potential energy, no pressure drops for flow through heat exchangers, and chemical exergy is not considered.

Table 2 shows the values of the mass flow rate ($\dot{m}$), specific exergy (b), pressure (P), and temperature (T) of water/steam flows. It is important to note that these are the optimal values for minimizing the objective function, which will be detailed in Section 3. This operating condition will be called the base case. Conventional mass, energy, and exergy balance equations are applied from the data to each control volume. The simulation is done in the Engineering Equation Solver [28]. The electricity sold (E_v) is the difference between the electricity produced and the internal consumption. In the base case, $E_v = 83{,}948$ kW, and the heat exchange in the condenser (Q_{conE}) is 35,709 kW.

Table 1
System parameters [26,27].

Parameter	Symbol	Value	Unit
Boiler efficiency	η_{Boiler}	86.23	%
Steam temperature	T_1	480	°C
Pressure levels	P_1, P_3, P_5, P_7	63, 11, 2.5, 0.2	bar
Turbine isentropic efficiency	η_T	83.20	%
Pump isentropic efficiency	η_{PMP}	85	%
Alternator efficiency	$\eta_{Alternator}$	98	%
Environment pressure	P_0	1	bar
Environment temperature	T_0	25	°C
Bagasse mass flow rate	$\dot{m}_{bag}$	< 77.778	kg/s
Boiler steam mass flow rate	$\dot{m}_1$	< 260	kg/s
High-pressure turbine mass flow rate	$\dot{m}_2$	< 220	kg/s
Medium-pressure turbine mass flow rate	$\dot{m}_4$	< 190	kg/s
Low-pressure turbine mass flow rate	$\dot{m}_6$	< 20	kg/s

Table 2
Thermodynamic properties of the physical flows of the cogeneration system.

Flow	ṁ kg/s	P bar	T °C	b kg/kJ
1	184.74	63.00	480.00	1350.37
2	184.74	63.00	480.00	1350.37
3	184.74	11.00	266.85	909.65
4	156.33	11.00	266.85	909.65
5	156.34	2.50	130.83	620.49
6	16.65	2.50	130.83	620.49
7	16.66	0.20	60.07	233.71
8	0.00	63.00	480.00	1350.37
9	0.00	11.00	450.60	1116.92
10	28.40	11.00	266.85	909.65
11	139.69	2.50	130.83	620.49
12	19.63	11.00	266.85	909.65
13	0.00	11.00	266.85	909.65
14	8.77	11.00	266.85	909.65
15	9.57	11.00	184.10	832.05
16	9.57	1.50	90.00	26.02
17	0.00	2.50	253.34	709.64
18	139.69	2.50	130.83	620.49
19	140.18	2.50	127.44	618.60
20	140.18	1.50	90.00	26.02
21	140.18	5.00	90.04	26.39
22	9.57	5.00	90.04	26.39
23	16.65	0.20	60.07	7.93
24	16.65	5.00	60.11	8.42
25	186.02	5.00	151.87	90.07
26	184.74	5.00	151.87	90.07
27	0.49	5.00	151.87	90.07
28	0.80	5.00	151.87	90.07
29	0.80	13.00	151.99	90.99
30	184.74	63.00	152.77	96.74

3. Optimization

In the realm of existing energy systems, parametric optimization at the operational level is a critical pursuit in economic optimization. The objective function in this context meticulously incorporates all operational costs stemming from system inputs, contingent upon decision variables. Equality restrictions are imposed on energy demands, steering the optimization method independently of any analyst-driven decisions regarding part-load operation strategies for the plant. Once the optimization problem is formulated and implemented, an automatic procedure takes charge of solving it, offering a set of operating instructions for each piece of equipment. These instructions aim to satisfy energy demands while minimizing operational costs.

Crucial to this optimization endeavor are the prices of bagasse (p_{bag}) and electricity (p_{ele}), integral components of an economic objective function. Assuming the plant is already in place, the primary goal is to delineate the optimal mode of operation for meeting energy service demands. The objective function seeks to minimize operating costs (C_{ope}[R\$/h]), Eq. (1).

$$Min\ C_{ope} = p_{bag} \cdot F_E - p_{ele} \cdot E_v \tag{1}$$

where F_E [kW] represents the bagasse consumption (LHV) and E_v [kW] the sale of electricity.

Determining the monetary cost of sugarcane bagasse is challenging due to the lack of a pre-established market for its purchase and sale. To estimate its cost, an approach was conducted, considering its exergy and the price of sugarcane. Beginning with a stipulated cost of 142.69 R$/ton of sugarcane and considering its composition, the estimated value of sugarcane bagasse is 70.38 R$/ton. Using the lower calorific value (LHV) and exergy (b) of sugarcane bagasse (7500 kJ/kg and 9941 kJ/kg, respectively), the estimated unit monetary cost of sugarcane bagasse was determined: p_{bag} = 0.0340 R$/kWh (LHV) = 0.02565 R$/kWh (b). Surplus electricity sold to the grid has been priced at p_{ele} = 0.1836 R$/kWh.

The plant's operating constraints are the availability of bagasse, which is limited by the amount of sugar cane processed, and the capacity of the boiler and turbine bodies indicated in Table 1. A nonlinear programming model in LINGO [29] has been developed to minimize the hourly cost. In the base case, with the heat demands required for the process (energy: Q_{proE} = 328,000 kW, exergy: Q_{proB} = 83,068 kW) and refinery (energy: Q_{refE} = 23,000 kW, exergy: Q_{refB} = 7711 kW) sections of the plant, and the electrical demand (energy = exergy: E_d = 30,000 kW) required to operate the sugar cane mills and other equipment, the optimal operation state shown in Table 2 is obtained.

The bold lines in Fig. 1 are associated with active mass flow in the optimal operation, while the lighter lines are not. The resulting operating state meets the following conditions: i) all available bagasse is consumed, ii) neither the boiler nor the turbines are operating at total capacity, iii) the throttling valves remain inactive, and iv) an electricity sale (E_v = 83,948 kW) is produced.

With the price corresponding to the base case (p_{ele} = 0.1836 R$/kWh) the total cost is 4421 R$/h, and the marginal costs of the demanded services are as follows for the energy base (see coloured circles in Fig. 2): λ_{QrefE}= 0.0382 R$/kWh, λ_{QproE}= 0.0231 R$/kWh, λ_{Ed}= 0.1836 R$/kWh, and for exergy base (see coloured circles in Fig. 3): λ_{QrefB}= 0.1139 R$/kWh, λ_{QproB}= 0.0912 R$/kWh, and λ_{Ed} = 0.1836 R$/kWh.

Figs. 2 and 3 present comprehensive visualizations of the operating costs and marginal costs of energy services versus the selling price of electricity. The coloured circles in Figs. 2 and 3 represent the marginal costs of the demanded services for the base case in energy base (Fig. 2) and in exergy base (Fig. 3). Specifically, blue circles represent refinery-related costs, red circles represent process-related costs, and green circles represent internal electrical demand. The marginal gain from electricity is depicted on a scale of /10 in Fig. 2 purely for visual representation purposes. This scaling was chosen to allow for better comparison with other marginal costs presented in the graph. These figures demonstrate how the marginal costs of the demanded services increase with the selling price of electricity, providing valuable insights into the economic dynamics of the system.

An important aspect to consider is how the selling price of electricity affects the operation of the plant. The same operating status will be maintained if this price does not go below 0.124 R$/kWh. As seen in Figs. 2 and 3 when the selling price of electricity rises to 0.236 R$/kWh the revenue from electricity sales offsets the cost of all bagasse consumed.

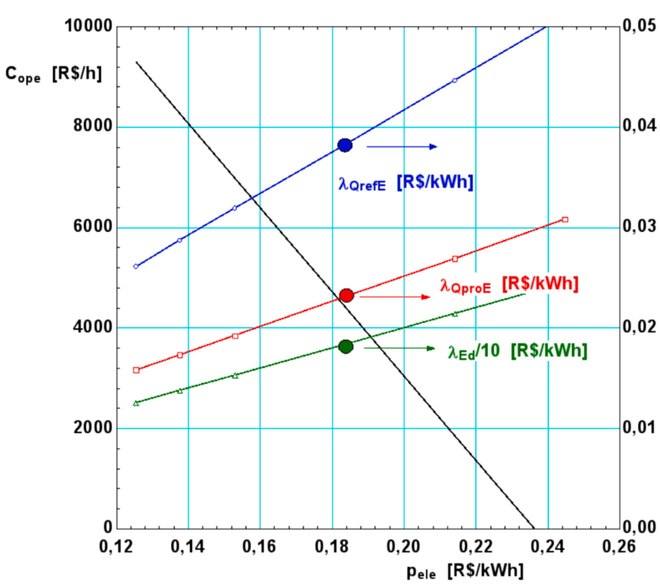

Fig. 2. Operating cost and marginal costs (energy base) of energy services vs. electricity selling price.

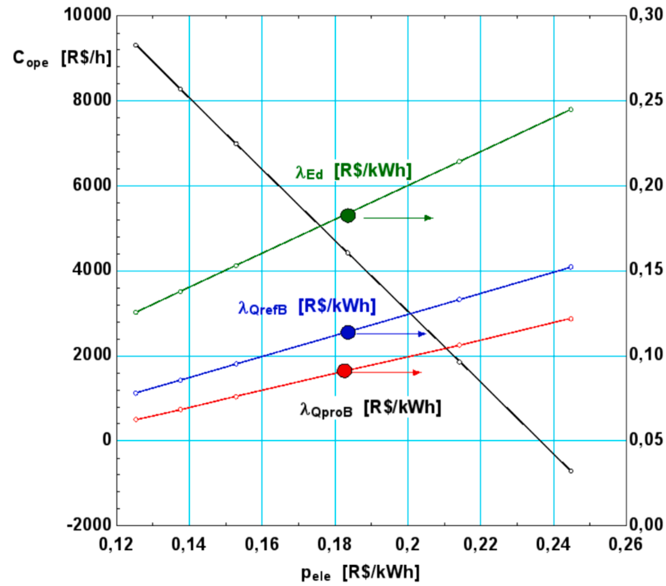

Fig. 3. Operating cost and marginal costs (exergy base) of energy services vs. electricity selling price.

Figs. 2 and 3 also show how the marginal costs of the demanded services increase with the selling price of electricity. Logically, additional electricity consumption means that electricity is no longer sold at the market price, so the marginal cost equals the selling price. As process heat demand increases, the additional steam demanded stops working in the subsequent turbine sections (MT and LT), decreasing electricity production and lowering sales revenues. Similar reasons justify that the marginal cost of refinery heat demand is higher than process heat demand. In essence, as the demand for process heat or refinery heat rises, a portion of the additional steam necessary ceases to effectively contribute to the work output in subsequent turbine sections (MT and LT). As a result, the diminished availability of steam for turbine expansion results in lower electricity generation and, consequently, a decline in sales revenue.

The solution of the optimization program provides the marginal costs associated with the model constraints. We have just analyzed the economic information associated with the demand constraints. Other marginal costs of interest are the following: a) if we had a larger quantity of bagasse available ($\dot{m}_{bag}$) at the same price (0.0340 R$/kg), b) if a steam flow rate $\dot{m}_9$ were imposed by the throttling valve (0.0155 R$/kg), and c) if a steam flow rate $\dot{m}_{17}$ were imposed by the throttling valve (0.0111 R$/kg).

Finally, with the analysis of results obtained from the operational optimization applied in this case study, it can be verified that the operation mode corresponding to the base case would remain unchanged (consuming all the available bagasse without reaching the capacity limit in the boiler and turbines, and with the throttling valves remaining inactive) as long as the plant's demand for energy services does not exceed the following individual limits. In the case of electricity consumption, the plant demand can be increased by an amount exactly equal to the electricity sold (E_v = 83,948 kW) at an additional cost equal to $\lambda_{Ed} \cdot E_v$ = 15,410 R$/h. The process steam consumption can be increased by $\Delta Q_{proE} \cong$ 40,000 kW at an additional cost of $\lambda_{QproE} \cdot \Delta Q_{proE} \cong$ 920 R$/h. The refinery steam consumption can be increased by $\Delta Q_{refE} \cong$ 45,000 kW with an additional cost of $\lambda_{QrefE} \cdot \Delta Q_{refE} \cong$ 1720 R$/h.

4. Thermoeconomic analysis

The thermoeconomic analysis study in this section is initiated based on a thermodynamic concept that allows the identification of subcycles in a thermal cycle [20]. Here, this approach consists of disaggregating the steam cycle of Fig. 1 into subcycles and analyzing them separately.

Observing the mass flows throughout the plant is necessary to identify these subcycles. In this case study, the thermal cycle can be disaggregated into three subcycles: cogeneration cycle generating work in the high-pressure turbine and refinery heat (Fig. 4); cogeneration cycle generating work in the high- and medium-pressure turbines and process heat (Fig. 5); and condensing cycle that generates only work in the high-, medium-, and low-pressure turbines (Fig. 6).

It is essential to reiterate that the explanation regarding the lines previously introduced at the beginning of this study applies equally to Figs. 4–6. In other words, the bold lines are associated with mass flows, thus emphasizing the subcycle under study. On the other hand, the thinner lines do not have associated mass flows, suggesting that the equipment connected to them may be considered inactive in the subcycle.

Once the set of disjoint subcycles that make up the operation carried out in the plant has been identified, it is necessary to determine the mass flow rates corresponding to the subcycles. These values can be observed in Table 3. A correct disaggregation of a cycle into subcycles must fulfill that the sum of the mass flows in the subcycles is equal to the total mass flow of the cycle. It can be verified that the performed disaggregation fulfills this condition by comparing the values in Tables 2 and 3.

After defining the subcycles, developing the productive structure for cost allocation becomes necessary. The productive structure clarifies the process of forming costs for the final products of the plant from the system fuel, as well as detailing the inputs and outputs of each subsystem. In this study, thermoeconomic analysis employs total exergy for defining productive flows and cost allocation.

It is worth noting that the dissipative equipment, the condenser, was merged and analyzed with the turbine in its corresponding subcycle (Subcycle 3). The productive structure shows arrows that indicate the productive flow path, and the rhombus and circles represent junctions and bifurcations, respectively. Both fictitious elements (rhombus and circles) do not present irreversibility, and rectangles represent the plant's equipment.

Figs. 7–9 presents the productive structure for the three subcycles. In each productive structure, it is possible to observe all the unit exergetic costs (in purple), the thermodynamic equations for the inputs and outputs (on an exergy basis), and their corresponding values (in yellow).

After defining the productive structure, each rectangle and rhombus are represented by an equation expressing its cost balance (Eq. (2)).

$$k^*_{out}\cdot\dot{B}_{out} = \sum\nolimits_{in} k^*_{in}\cdot\dot{B}_{in} \quad (2)$$

It is worth mentioning that each rectangle and rhombus presents only one product. Nevertheless, auxiliary equations are necessary when this product is divided into more than one flow. In these cases, the unit cost of the product is assigned to the different production flows coming from the division.

By solving the thermoeconomic model, the set of cost equations balances, the unit exergetic costs (k^*_{out}) can be determined. In the cogeneration system, the unit exergetic cost associated with the fuel (external) used by the boiler is fixed at $k^*_F = 1$ kJ/kJ. This practice aligns with principles in thermoeconomics, where the cost of external fuel is typically assumed to be equal to its exergy. Consequently, this assumption results in a unit exergetic cost of 1 kW/kW, reflecting the amount of exergy required to obtain one exergetic unit of that flow. It is also considered equal to 1 because there is no exergy destruction before the productive process is performed. This measurement serves as an indicator of the thermodynamic efficiency of the production process [12].

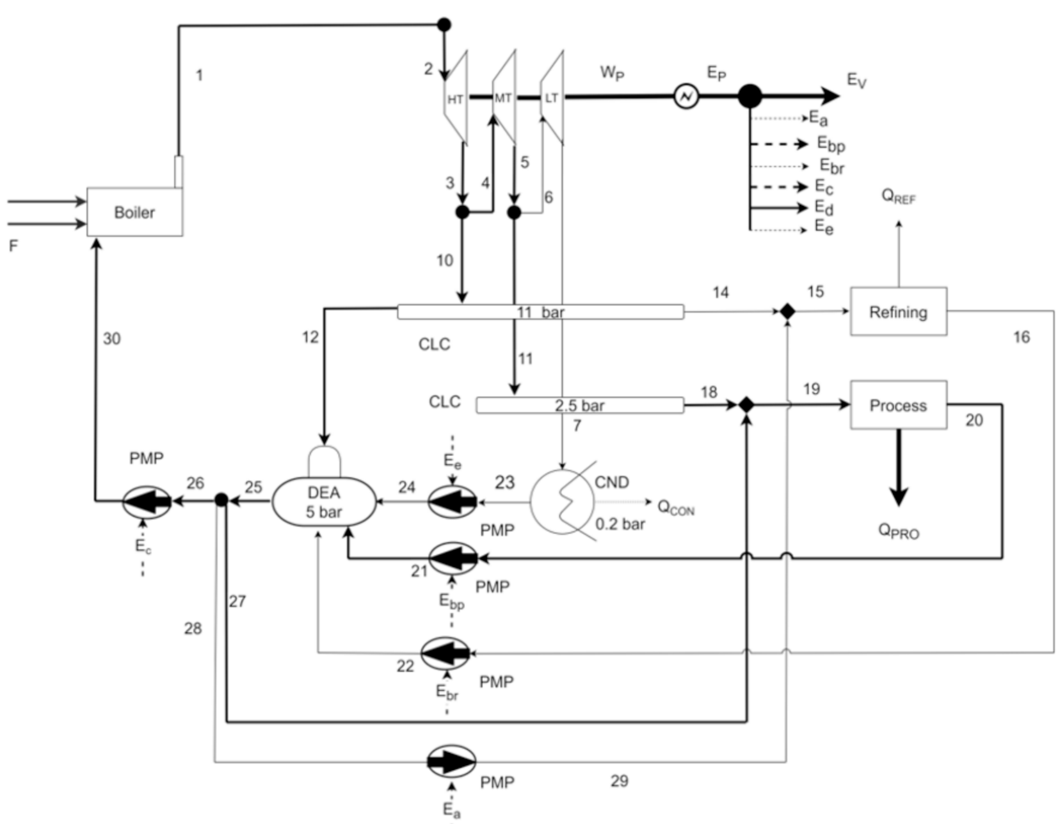

Fig. 4. Cogeneration cycle generating work and process heat (Subcycle 1).

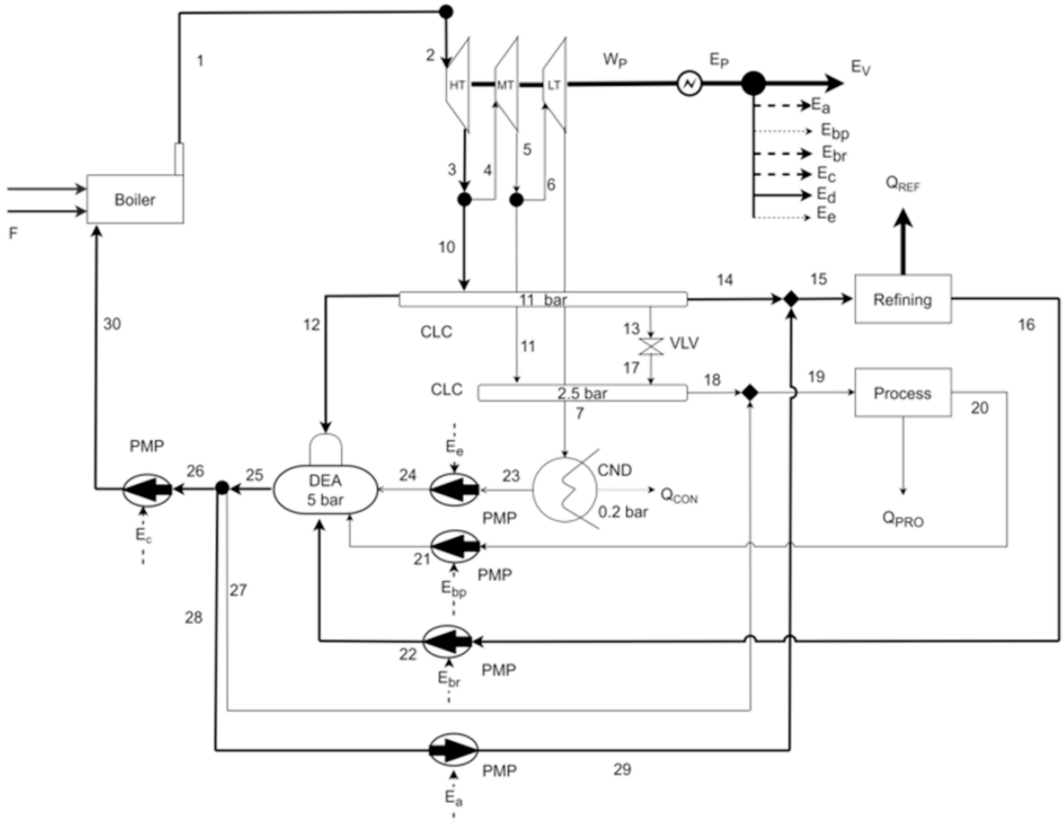

Fig. 5. Cogeneration cycle generating work and refinery heat (Subcycle 2).

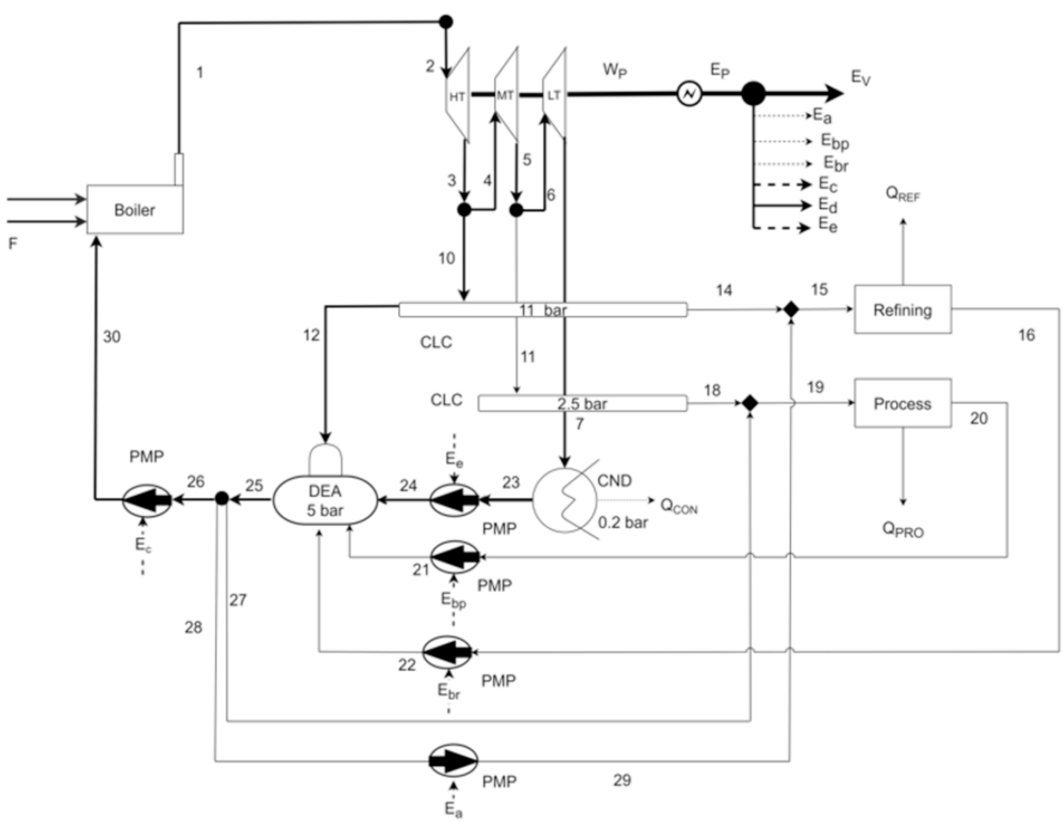

Fig. 6. Condensing cycle (Subcycle 3).

Table 3
Mass Flow [kg/s] in the cogeneration cycle and subcycles.

Mass Flow	Subcycle 1	Subcycle 2	Subcycle 3	Sum
$\dot{m}_1$	155.47	9.85	19.42	184.74
$\dot{m}_4$	139.69	0.00	16.65	156.33
$\dot{m}_6$	0.00	0.00	16.65	16.65
$\dot{m}_{10}$	15.79	9.85	2.77	28.40
$\dot{m}_{11}$	139.69	0.00	0.00	139.69
$\dot{m}_{12}$	15.79	1.08	2.77	19.63
$\dot{m}_{14}$	0.00	8.77	0.00	8.77
$\dot{m}_{15}$	0.00	9.57	0.00	9.57
$\dot{m}_{19}$	140.18	0.00	0.00	140.18
$\dot{m}_{25}$	155.97	10.64	19.42	186.02
$\dot{m}_{27}$	0.49	0.00	0.00	0.49
$\dot{m}_{28}$	0.00	0.80	0.00	0.80

Although the study has performed an individualized thermoeconomic analysis for each of the three subcycles, which allows for a more detailed understanding of the cost formation process, a fairer cost allocation, and the possibility of using different methodologies in subcycles that contain dissipative equipment, it is necessary to re-aggregate the subcycles into a single cycle to estimate the costs of the final products of the thermal system as a whole.

Fig. 10 illustrates the unit exergetic costs (k*) of the final products, namely heat for refinery Q_{refB}, electricity sold E_v, internally consumed electricity E_d, and heat for process Q_{proB}, which are a composition of the unit exergetic costs calculated in the subcycles and are as follows: $k^*_{QrefB} = 3.466$ kJ/kJ, $k^*_{Ev} = k^*_{Ed} = 4.060$ kJ/kJ, and $k^*_{QproB} = 3.417$ kJ/kJ.

Similarly, Fig. 11 shows the unit exergoeconomic costs of the final products, calculated as $c_j = k^*_j \cdot p_{bag} = k^*_j \cdot 25.651$ R\$/MWh, with values of $c_{QrefB} = 88.906$ R\$/MWh, $c_{Ev} = c_{Ed} = 104.133$ R\$/MWh, and $c_{QproB} = 87.662$ R\$/MWh.

Both figures use a color scheme to convey information, where the pink color represents the unit exergetic costs (k*) in Fig. 10 and the unit exergoeconomic costs (c) in Fig. 11. Additionally, the yellow color denotes the exergy value of the flow (B) in both figures. Finally, the blue color represents the exergetic cost ($B^* = k^* \cdot B$) in Fig. 10 and the exergoeconomic costs ($C = c \cdot B$) in Fig. 11.

After estimating the costs of the final products of each subcycle and presenting the composition of the exergoeconomic unit costs for the overall cycle in Fig. 11, an important question arises. If the electricity market purchases this electricity for a value higher than the cost estimated by thermoeconomic analysis, what should be the actual value attributed to the cost of electricity in allocating its costs?

Adopting the market value for the cost of electricity sold by the cogeneration system implies that the other products of the same plant will now have a lower cost. In other words, a discount must be applied to the other products of the plant since electricity now has a higher cost than the estimated cost by thermoeconomic methodology. Therefore, the question becomes: How to calculate this discount?

This section presents a possibility for measuring it. When comparing the selling price of electricity ($p_{ele} = 183.6$ R\$/MWh) in the Brazilian market, it is found that the cost of electricity ($c_{Ev} = 104.133$ R\$/MWh) estimated through thermoeconomic analysis is lower than the price in the Brazilian market. Therefore, it is natural for the company to charge sold electricity at market value, which automatically generates a discount (d) for the final internal products, which can be estimated from Eq. (3).

$$p_{bag} \cdot F_E - p_{ele} \cdot E_v = x_{QrefB} \cdot Q_{refB} + x_{Ed} \cdot E_d + x_{QproB} \cdot Q_{proB} \tag{3}$$

where $x_j = (1 - d) \cdot c_j$.

Figs. 12 and 13 present the results of a parametric variation of the unit electricity selling price (p_{ele}) and its relation to the respective discount, as well as the monetary costs per unit of energy (Fig. 12) or per unit of exergy (Fig. 13) of the final internal products.

Specifically, for the electricity cost ($p_{ele} = 0.1836$ R\$/kWh), a discount d ≅ 60 % is obtained, resulting in monetary costs per unit of exergy of the final internal products as follows: $x_{QrefB} = 0.03544$ R\$/kWh, $x_{Ed} = 0.04151$ R\$/kWh, and $x_{QproB} = 0.03494$ R\$/kWh. With the same discount, the monetary costs per unit of energy are: $x_{QrefE} = 0.01188$ R\$/kWh, $x_{Ed} = 0.04151$ R\$/kWh, and $x_{QproE} = 0.00850$ R\$/kWh.

As the value of the unit monetary cost of electricity sold increases, the discount also increases, decreasing the monetary cost of the final products depicted in both graphs. When comparing the monetary costs of refinery heat and process heat (final products), it is possible to observe that the difference between these costs is more significant in terms of energy than exergy. However, overall, it is possible to follow that the trend of the lines is the same in both graphs.

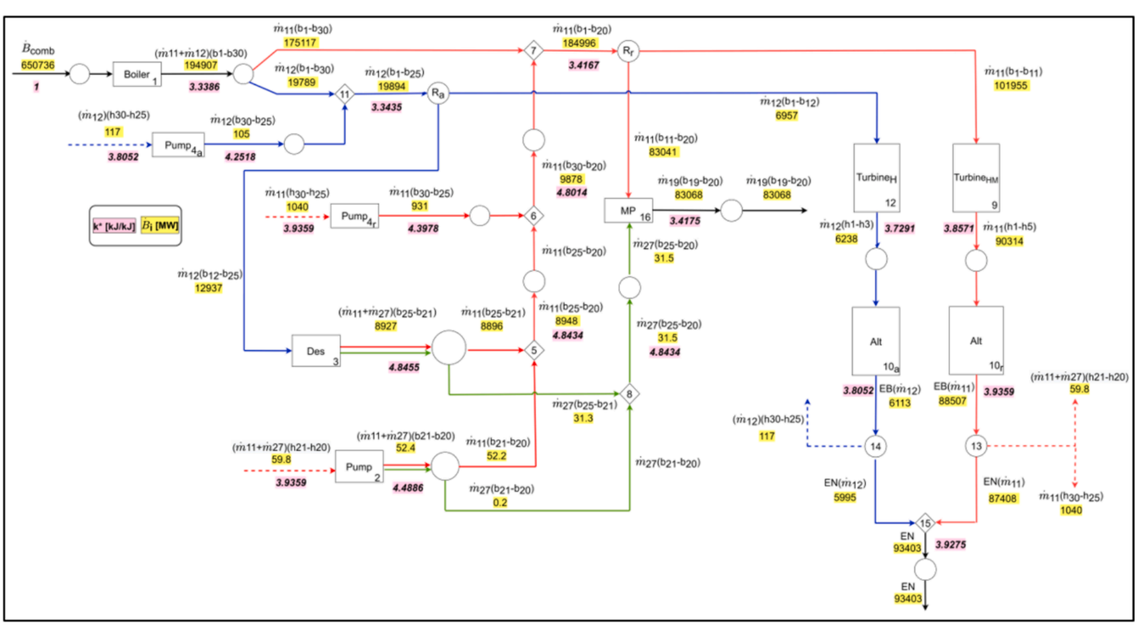

Fig. 7. The productive structure of the cogeneration cycle generating work and process heat.

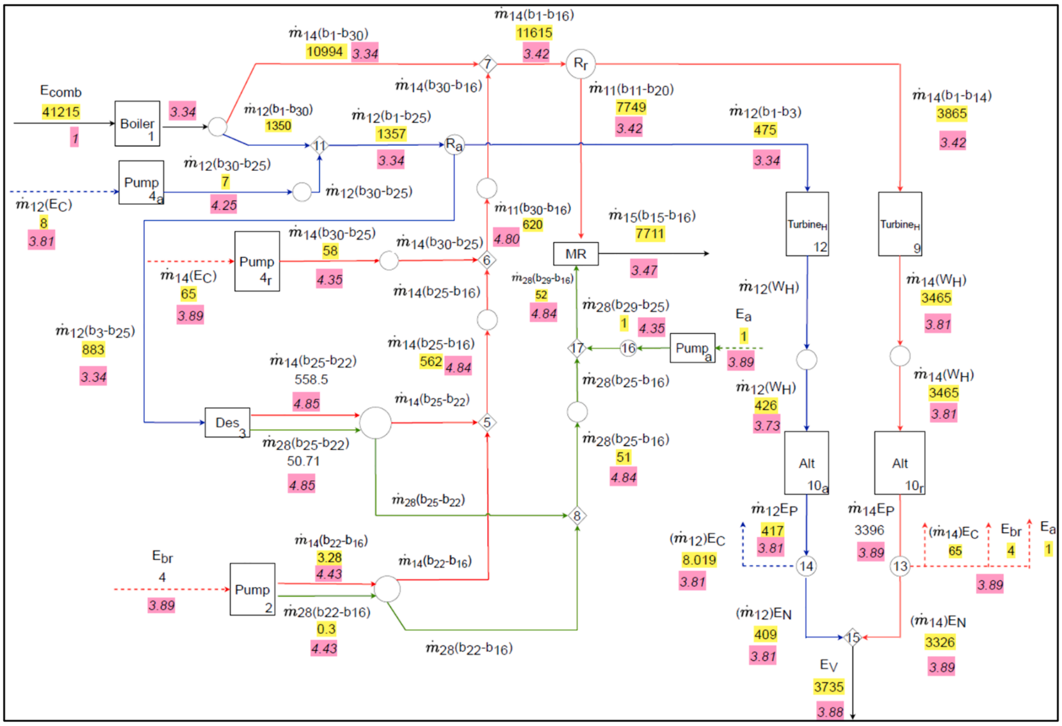

Fig. 8. The productive structure of the cogeneration cycle generating work and refinery heat.

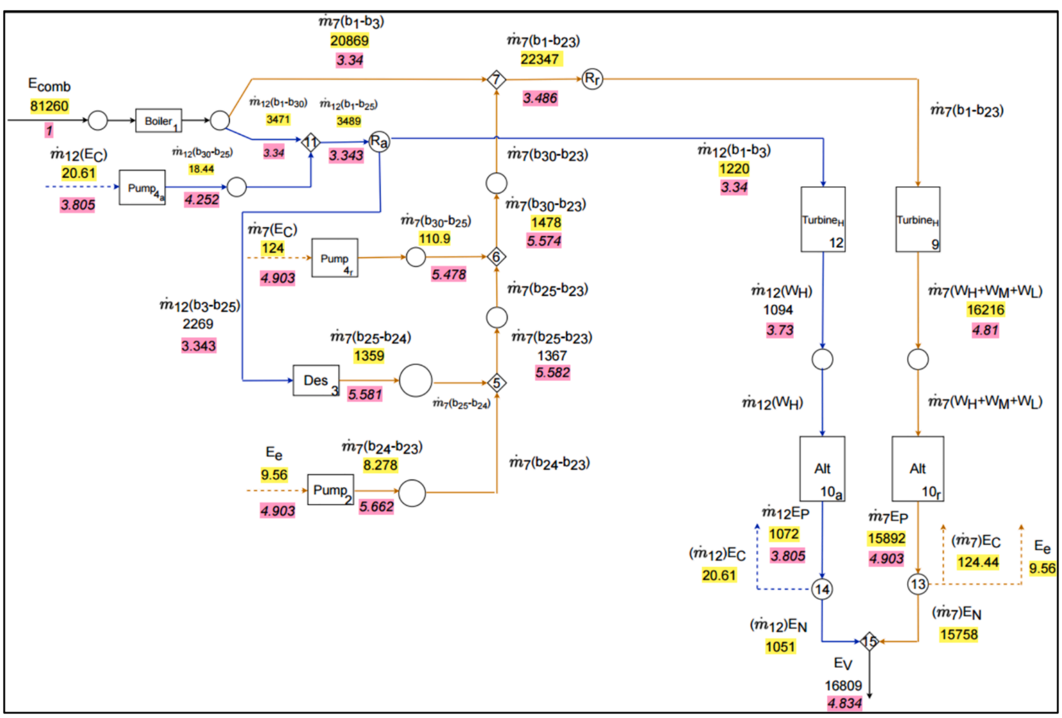

Fig. 9. The productive structure of the condensing cycle.

5. Conclusions and closure

In this study, a comprehensive energy billing optimization and thermoeconomic analysis of a sugarcane steam cogeneration plant was carried out.

The optimization model developed in the study determined the optimal mode of operation of the cogeneration plant and provided not only the operating status and economic cost, but also the marginal economic costs of the final products, which allowed to assess limitations in the availability of bagasse, additional product demands and changes in the price of electricity sold to the grid. In the case under analysis, the minimum cost necessary to satisfy the energy services demanded (Q_{proE} = 328 MW, Q_{refE} = 23 MW, and E_d = 30 MW) is 4421 R$/h. All available bagasse (280 t/h) is consumed and the excess of electricity produced is sold to the grid (E_v = 83.95 MW). Marginal product costs, on an energy basis, obtained with the optimization program (λ_{QproE} = 23.1 R$/MWh,

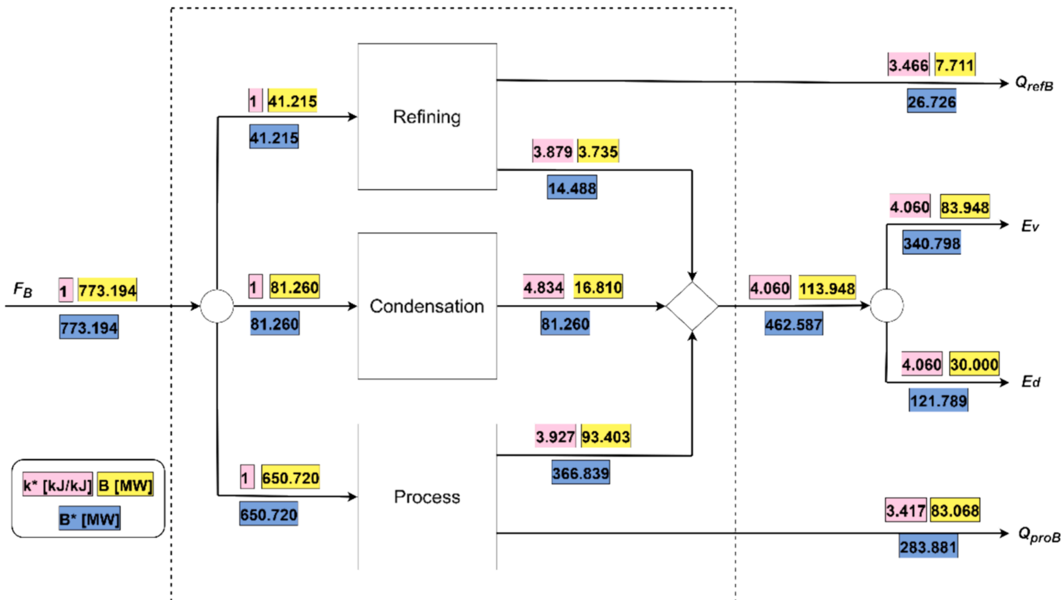

Fig. 10. The productive structure with the main flows for the re-aggregated thermal system (unit exergetic costs).

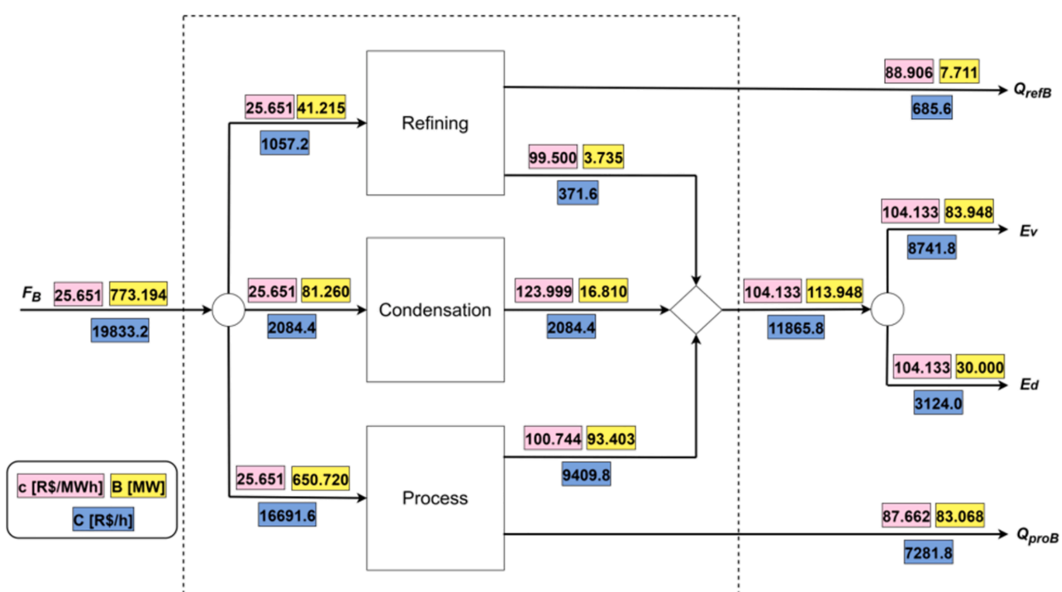

Fig. 11. The productive structure with the main flows for the re-aggregated thermal system (unit exergoeconomic costs).

λ_{QrefE} = 38.2 R$/MWh, and λ_{Ed} = 183.6 R$/MWh) reveal a great difference in economic value per unit of energy of the three products obtained. These costs on an exergy basis (λ_{QproB} = 91.2 R$/MWh, λ_{QrefB} = 113.9 R$/MWh, and λ_{Ed} = 183.6 R$/MWh), although different, do not show that much difference. With the same energy demand the analysis showed that the operating status would remain the same as long as the selling price of electricity did not fall below 124 R$/MWh. The study also demonstrated how the marginal costs of energy services increase with the selling price of electricity and provided information on the limits of the plant's demand for energy services. In particular, the interest of having these marginal costs in the management of steam plants has already been highlighted by other authors before [30,31], as well as in district heating systems [32] and trigeneration systems including thermal storage [33].

A thermoeconomic analysis was performed identifying that the operation of the plant involves the overlapping of three subcycles and defining their production structures. This disaggregation allowed the assignment of costs per unit of exergy to the plant's internal flows and final products. The study also presents the composition of the unit monetary costs of the re-aggregated thermal system. Specifically, the unit monetary costs of final products on an energy basis are as follows: heat for the process (c_{QproE} = 22.2 R$/MWh), heat for the refinery (c_{QrefE} = 29.8 R$/MWh), and internally consumed electricity and electricity sold (c_{Ed} = 104.1 R$/MWh).

The cost of electricity estimated through thermoeconomic analysis it is found that is lower than the selling price in the Brazilian market (p_{ele} = 183.6 R$/MWh). Therefore, it is natural for the company to charge sold electricity at market value, which automatically generates a discount for the final internal products consumed in the plant. Applying the same discount to all of them leads to the following costs on an energy basis: heat for the process (x_{QproE} = 8.4 R$/MWh), heat for the refinery (x_{QrefE} = 11.9 R$/MWh), and internally consumed electricity (x_{Ed} =

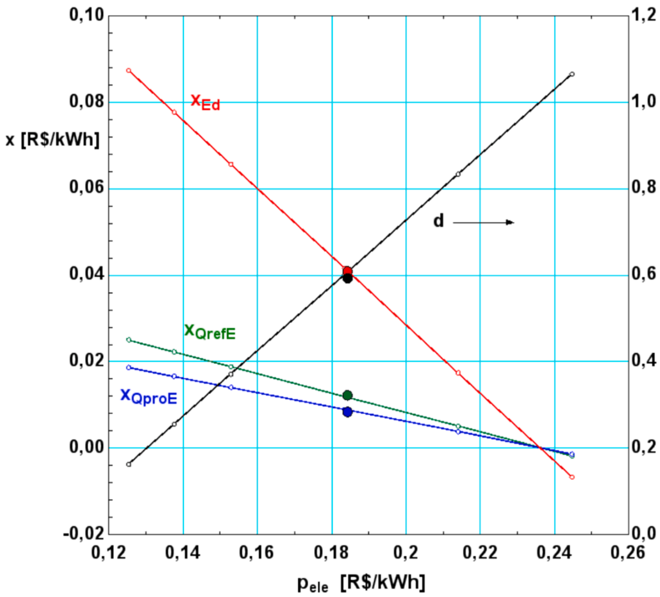

Fig. 12. Unit cost allocated to energy services (energy base) vs. electricity selling price.

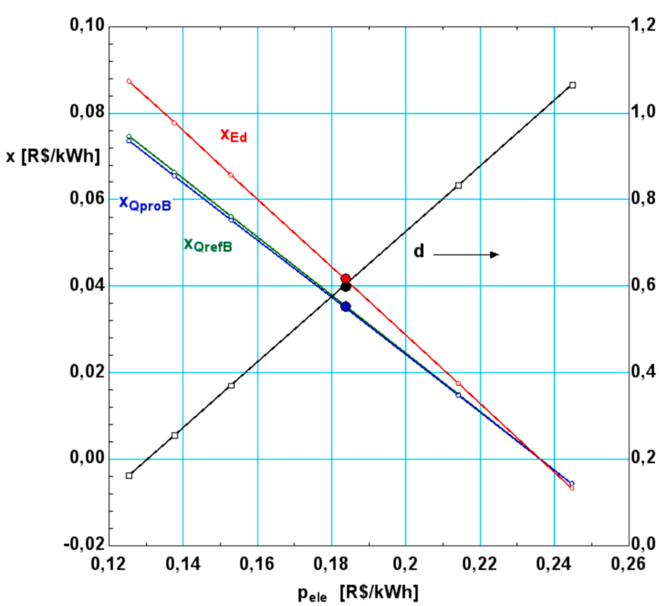

Fig. 13. Unit cost allocated to energy services (exergy base) vs. electricity selling price.

41.5 R$/MWh).

Overall, the study, conducted in a Brazilian sugarcane power plant, is replicable with appropriate considerations in any other power plant with a steam cogeneration system. It demonstrates that the combination of thermoeconomic analysis and mathematical optimization allows increasing the efficiency of energy processes and helps to answer specific energy management questions. The results obtained improve the understanding of the cost formation process, support a fair cost allocation and provide insight into the use of different sub-cycles to obtain the optimal output. The combination of thermoeconomic analysis and mathematical optimization thus offers a dual perspective to answer specific questions related to energy management, such as the future planning of the operation of CHP plants and the monitoring of the cost formation of the different products obtained.

CRediT authorship contribution statement

Miguel A. Lozano: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rodrigo dos Santos:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **José J.C.S. Santos:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis. **Luis M. Serra:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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