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THERMOECONOMIC ANALYSIS OF A SUGARCANE PLANT COGENERATION SYSTEM UNDER DIFFERENT THERMAL INTEGRATION LEVELS

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Abstract. *The cogeneration system is the most important sector in sugarcane mills, providing energy for sugar, alcohol and electricity production, the latter being responsible for self-sustainable generation and selling the surplus to the grid. Improving overall efficiency has always been a common goal in mills, and thermal integration is a great technique for optimizing the plant's energy consumption, since it performs a thermal exchange between the process streams and reduces successive losses from it. To evaluate the system thermoeconomic is applied, based on exergy and economy concepts, where the formation process of exergetic and monetary costs is analyzed, relating them to the plant fuel, being more accurate than isolated exergetic and financial evaluations. The analysis in this paper will be performed using the E and H&S thermoeconomic models, in order to identify and quantify the impact of thermal integration on the system final products costs, useful heat and electricity. The exergetic or monetary results are represented on a solution straight line with ordered pairs of own products costs, with the process steam consumption changing, due to integration level, new straight lines will be generated, once these are associated with the ratio of the final products and the overall exergetic efficiency. The application of thermal integration presents higher costs, despite providing an increase in process efficiency, which ultimately confirms the potential for improvement and reiterates the importance of exploring new methods for the rational steam utilization even though it is more expensive.*

Keywords: *Thermoeconomic, Exergy, Thermal integration, Sugarcane plant.*

1. INTRODUCTION

Sugar cane has significant participation in Brazilian agriculture, being considered one of the most notable alternatives in the biofuel's scenario due to the great ethanol production capacity among other products. As well as electric power, there is also the useful heat production for the sugar factories process, resulting in mainly sugar types and alcohol types. The Brazilian energy matrix in the year 2020 had a contribution of 65.2 % from hydraulic sources, 8.8 % wind energy 9.1 % biomass, 8.3 % natural gas, 2.2 % nuclear, 2.7 % coal, 2.1 % petroleum products and 1.7 % solar (EPE, 2021a). The biomass present in the matrix is composed mainly of sugarcane bagasse, around 82 %, and in 2020 harvest the total amount of processed cane was 663 million tons, originating the ethanol production of 32.6 billion liters and 41.5 million tons of sugar (EPE, 2021b).

The sugarcane plant cogeneration systems are continuously aiming the electricity production for sale. As an example, from the 361 sugarcane factories that are producing in Brazil, 230 export energy to the SIN (Sistema Nacional Interligado), therefore, the search for improvement in the processes aiming the energy consumption reduction is gradually increasing. There are some techniques that reduce the process steam consumption, thermal integration shows great potential for improvement about this consumption, providing the heat exchange maximization between process flows, as well as the minimum effluents and emissions output and maximum power generation (Ensinas, 2008).

The thermoeconomic application in thermal systems can be summarized into three evaluation modes: diagnostic analysis, where the main objective is to find the causes and assess the impact on energy consumption of a given additional irreversibility (Valero *et al.*, 2004); optimization analysis, which selects the most efficient plant associated with the lowest initial investment, beyond the definition of the cheapest and most efficient operational strategies; and finally, cost allocation, which according to Faria (2014) is the best way to compare and evaluate thermoeconomic methodologies, due to the fact that it is the application field that requires the main premises definition on which the discipline is based: product cost formation process, by-products and wastes, fuel, product, purpose, cause, efficiency, etc. This methodology combines

exergetic and economic concepts to quantify and price the costs of final products, in sugarcane plant cogeneration system case, thermo-economic identifies the cost of useful heat and electric power for the plant, either exergetic or monetary. There are different thermo-economic models that are applied according to the flows and equipment of the thermal system, this evaluation uses the E model, which is based on exergy and the H&S model, which in turn disaggregates the exergy into enthalpy and entropy components.

This paper aims to perform a thermo-economic evaluation of a sugarcane plant cogeneration system under different thermal integration levels in the process. The analysis will be performed applying E and H&S thermo-economic models in three scenarios, first with thermal integration totally absent, then its implemented at an intermediate level for observation of the final products costs throughout the evolution, and finally in highest level.

2. METHODOLOGY

2.1 Cogeneration system description

The analyzed thermal cycle, as previously mentioned, is a sugarcane plant cogeneration system, where there is useful heat for the process and electricity as final products, being basically a steam Rankine cycle using an extraction condensing turbine, as shown in Figure 1. The boiler is fed by sugarcane bagasse and generates 260 t/h of superheated steam, which is destined for the turbine to produce electricity by a coupled generator, with the steam expansion to the pressure of 2.5 bar, necessary for the process, and the rest to the vacuum pressure. There is a by-pass line in the extraction for the process, being used to maintain the outlet temperature of the deaerator constant, independent of the deaerator inlets by the other streams, because it will be changed throughout the plant simulation. The hours worked per harvest is 4000 h and the total amount of processed cane in the study plant is 2 Mt (Ensinas *et al.*, 2007). Furthermore, to make the cycle more realistic, energy consumption by the boiler and pumps are considered, being 2 kWh/t of cane for the boiler, 0.02 kWh/t of cane for pump I and 1.3 kWh/t of cane for pump II. The operating and complementary parameters for each point in the plant are described in Tables 1 and 2, which are pressure, temperature, enthalpy, entropy and specific exergy.

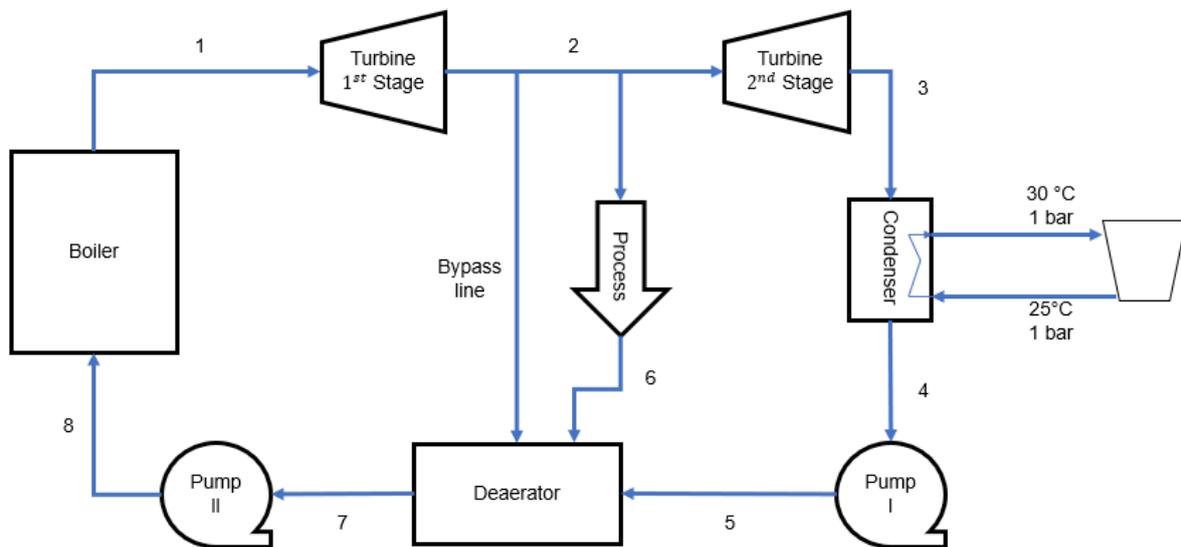


Figure 1. Sugarcane plant cogeneration system.

Table 1. Plant operation parameters.

Point	P (bar)	T (C°)	h (kJ/kg)	s (kJ/kg.K)	e (kJ/kg)
Ref.	1.013	25	104.8	0.3669	0
1	65	480.0	3368	6.774	1353
2	2.5	127.4	2758	7.153	629.8
3	0.14	52.56	2399	7.428	189.3
4	0.14	52.56	220	0.7367	4.932
5	2.5	56.58	220.3	0.7369	5.177
6	2.5	127.4	535.5	1.608	60.76
7	2.5	127.4	535.5	1.608	60.76
8	65	128.4	543.8	1.612	67.85

Table 2. Complementary parameters of the cogeneration system.

Description	Value
Boiler outlet steam pressure	65 bar
Boiler outlet steam temperature	480 °C
Turbine and pumps isentropic efficiency	80 %
Generator efficiency	96 %
Process steam pressure	2.5 bar
Process steam temperature	127.4 °C
Harvest sugarcane processed	2000000 t
Harvest worked hours	4000 hours

Thermal integration in sugarcane plants has been an important resource when it comes to rational energy utilization, because in the production process there are flows that need to be cooled, such as the must and the steam condensate as well as others that need to be heated, such as the treated juice entering the evaporator and the fermented liquor. There is also the use of stillage heat in the distillery, which did not happen in the older plants, since this is a waste stream (Pina *et al.*, 2014). In this paper, the thermoeconomic evaluation is in function of steam consumption by the process, meaning that the lower of thermal integration level, higher will be the steam consumption.

The consumption variation made in this analysis aims at comparing a typical Brazilian mill without thermal integration and a thermally integrated mill at maximum level, beyond an intermediate consumption to clarify the results behavior. By analyzing the steam consumption of sugar and alcohol production in different phases, it is possible to determine how much steam each phase receives. Relating these portions to the total process consumption, it is obtained values for the juice heating phase of 26.1%, evaporation of 21.7%, boiling of 14%, fermented juice heating of 11.2%, distillation of 26.9% and sugar drying of 0.1% (Ensinas *et al.*, 2007).

According to Rein (2007), the process steam consumption in most mills is around 500 kg/t of sugarcane, and the minimum consumption is around 350 kg/t of sugarcane, with a high level of thermal integration. However, (Ensinas *et al.*, 2008) and (Pina *et al.*, 2015), show that consumption values in the 280 kg/t sugarcane range can be obtained with some improvements, such as electrification of the mills, increasing the solid content of the syrup in the evaporator from 65 % to 72 %, reducing the boiling pans consumption and increasing the vapour amount that can be used to heat the treated juice and fermented liquor, besides the heat recovery that can be obtained with the streams that will be cooled as condensate, vinasse and must.

With the process steam consumption established, the study cases are determined, presented in Table 3, and simulated in the Engineering Equation Solver (EES).

Table 3. Process steam consumption evaluated.

Study cases	Consumption (kg/t of sugarcane)
Case I	500
Case II	350
Case III	280

2.2 Exergetic analysis of sugarcane bagasse

The boiler fuel and main input of the plant is the sugarcane bagasse, then chemical exergy is defined to obtain the contribution to the system. There are methodologies to characterize wood exergy (Szargut *et al.*, 1988), one of them described in Equations (1) and (2), and according to Sosa-Arno and Nebra (2005), this definition is satisfactory because the sugarcane bagasse composition is similar to wood, basically composed of cellulose, hemicellulose and lignin. The dry base sugarcane bagasse mass composition is shown in Table 4, as well as its lower heating value (LHV) for a 50 % moisture (Cavalcanti *et al.*, 2020).

Table 4. Sugarcane bagasse parameters.

Description	Value
LHV	7034 kJ/kg
Carbon	44.80 %
Hydrogen	5.40 %
Oxygen	39.60 %
Nitrogen	0.40 %
Sulfur	0.01 %
Ash	9.79 %

In this way, the bagasse specific exergy is determined.

$$e_{bagasse} = \beta(LHV + Wh_{LV}) + e_w W \quad (1)$$

$$\beta = \frac{1,0412 + 0,2160 \frac{H}{C} - 0,2499 \frac{O}{C} (1 + 0,7884 \frac{H}{C}) + 0,0450 \frac{N}{C}}{1 - 0,3035 \frac{O}{C}} \quad (2)$$

where W is the bagasse moisture, h_{LV} the water vaporization enthalpy, e_w the water specific exergy and H, C, O e N the percentages of Hydrogen, Carbon, Oxygen and Nitrogen respectively.

To calculate the exergetic efficiency of the plant, Equation (3) is used, where the efficiency between the different steam consumption parameters will also be compared.

$$\eta_{exegetic} = \frac{(\dot{W}_{net} + \dot{Q}_U)}{\dot{Q}_{Bagasse}} \quad (3)$$

where \dot{W}_{net} is the electricity to the grid, \dot{Q}_U the useful heat allocated to the process on an exergetic basis, and $\dot{Q}_{Bagasse}$ the exergy added by bagasse burning on an exergetic basis too.

2.3 Thermoeconomic

Thermoeconomic combines thermodynamic and economic concepts to quantify and price the thermal systems flows, going further than a common energy and economic analysis, achieving extremely important information for such systems (Valero *et al*, 2006). Once the cogeneration system is configured, the thermoeconomic methodology is applied in order to build the production structures, which determine the fuels and products of each equipment, while analyzing the exergetic and monetary costs formation process, minimizing plant total cost and verifying the costs of different products from the same process (Tsatsaronis and Valero, 1989). Some methodologies use total exergy, through the E model, to define the production structure, while others perform the disaggregation into enthalpic and entropic components, through the H&S model, making the analysis more accurate because for certain equipment, called dissipative equipment such as the condenser and valve, there are no well defined products and make the association between equipment necessary.

In E model, when the exergetic flows that pass through an equipment increases, they are products, thus they are being produced by the equipment, however, if they are decreasing, they are fuels. Faria (2014) describes how production flows are defined as a function of physical flows, and the change in exergy ($E_{i,j}$) is represented by the difference between two flows (i e j).

$$E_{i,j} = E_i - E_j \quad (4)$$

This model requires the association of the condenser to the turbine in the evaluated cogeneration system, since it is a dissipative equipment and has no product, not allows a thermoeconomic isolation and an association is necessary. Figures 2 presents the E model production structure, where the productive flows are defined through physical flows and the real equipment is connected by fictitious equipment, called junctions and bifurcations.

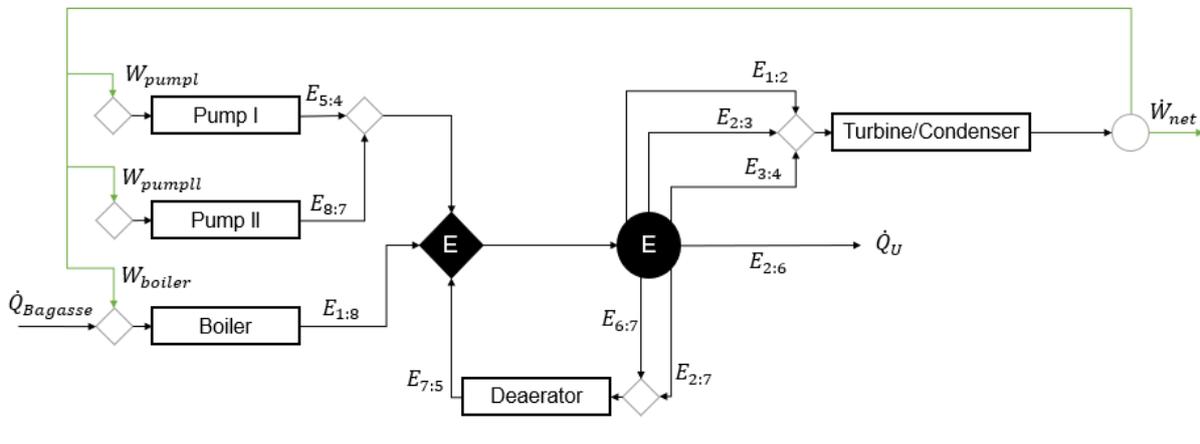


Figure 2. E model production structure.

Table 5. Equipment costs of the cogeneration system and sugarcane bagasse.

Description	Cost (R\$)
Sugarcane bagasse (ton)	59.22
Boiler	48720000.00
Condensate Pump	174000.00
Boiler Pump	3132000.00
Deaerator	3480000.00
Condenser	1392000.00
Turbine	29580000.00

The equipment costs also need to be corrected by the amortization factor and the operation and maintenance factor. The annual cost percentage associated with the second is considered to be 7 %, while for the amortization factor it is necessary to determine the number of years of plant operation, as well as the annual interest rate, 15 years and 12.4 % respectively. The amortization factor is calculated as follows.

$$\xi = \frac{(i+1)^{n_a}}{3600n_a n_h ((1+i)^{n_a} - 1)} \quad (9)$$

where i represents the annual interest rate, n_a years of operation, and n_h hours worked per year. The final value of fuel and equipment is determined by Equation (10).

$$\dot{Z}_{equip} = z_{equip} \xi \varphi \quad (10)$$

where z_{equip} is the equipment cost without correction and φ is the operation and maintenance factor.

With the determination of all the costs, it is possible to perform the monetary equation, very similar to Eq. (8), and also being performed for each equipment in the cogeneration system.

$$c_p P - c_f F = \dot{Z}_{equip} \quad (11)$$

where c_f is the equipment fuel unit monetary cost, F fuel value on an exergetic basis, c_p flow unit monetary cost after the equipment, and P product value also on an exergetic basis.

The product final costs will be presented in ordered pairs of useful heat and electricity on a solution straight line, this straight line being limited by the maximum unit costs of the products when they are produced separately, in other words, there is no cogeneration. According to Santos *et al.* (2016) the results should be located along this straight line regardless of the thermoeconomic model applied.

3. RESULTS

The results of this work present the change in final products costs related to the consumption of process steam applying the thermoeconomic. Thus, the analysis is done demonstrating the impacts of switching consumption, as well as the deviations of results between the E and H&S models.

The sugarcane bagasse specific chemical exergy found with the compositions mentioned previously was 8014 kJ/kg and the exergy added by it was 280496 kW.

Initiating with Case I, where there is the lowest level of process integration and consequently the highest steam consumption, the cogeneration system obtained 39269 kW of electricity surplus and 39517 kW of useful heat, destined for the sugar and alcohol production process, the exergetic efficiency associated with this Case was 28.09 %. The exergy and monetary costs for all models are presented in Table 6.

Table 6. Exergetic and monetary unit costs.

		Exergetic (kW/kW)		Monetary (R\$/MWh)	
		Useful heat	Electricity	Useful heat	Electricity
Case I	E Model	3.080	4.044	83.59	111.8
	H&S Model	3.093	4.030	83.99	111.4
Case II	E Model	3.099	4.286	84.11	118.1
	H&S Model	3.219	4.213	87.40	116.1
Case III	E Model	3.108	4.381	84.35	120.6
	H&S Model	3.280	4.302	89.07	118.4

The unit exergy cost of electricity is higher in the E model, due to the association between the turbine and the condenser to enable the use of this model, since the condenser has no product. In this way, the input of the electric power producing equipment is overcharged by the input of the dissipative equipment, so the cost of this product increases.

In the H&S model the exergy is disaggregated, enabling the isolation of all the equipments, including the dissipative, thus has a more accurate analysis of the final products costs, as the electricity comes only from the turbine in this model, it will be cheaper. And even considering the monetary cost of the equipment, the electricity cost still stands out in the E model. Results that will be repeated in the other Cases.

For Case II, the cogeneration system produces 45441 kW of surplus electricity and 27622 kW of useful heat, the exergetic efficiency considering the process consumption of 350 kg/t of cane was 26.06 %. The exergetic and monetary costs of model E in this Case are still more expensive, due to the same problem that the condenser presents because it has no product, which makes the H&S model results more accurate. All costs were increased with the change in steam consumption by the process, both exergetic and monetary, despite applying thermoeconomic to cogeneration systems, normally the cost of one product increases and the cost of another product decreases, it means that the cost of electricity would increase and the useful heat would decrease, and vice versa. Such behavior is expected to occur when parameter change is involved in the thermoeconomic methodology, like as switching the models applied. Higher excess electricity production is expected as the process steam requirement decreases, exergetic efficiency is also decreased due to the reduction in useful heat being higher than the increase in electricity surplus, due to the turbine and generator irreversibilities, that destroys exergy when turn that into electric power, thus the steam that is driven to the turbine in accordance with the demand reduction in the process is not fully converted.

In the best steam consumption of the process, Case III, the production of electricity and useful heat was 48322 kW and 22129 kW respectively, and the exergetic efficiency 25.12 %. In the last Case there is again an increase in all the costs, and the largest increase is the unit exergy cost of electricity in model E, reiterating that the increase and decrease between the cost of the different products will be respected only inside the thermoeconomic methodology. The exergetic efficiency is again decreased in this Case because the equipments irreversibilities.

To better understand the results, Figures 4 and 5 show the solution straight line of unit costs, when it is said that the cost of one product will increase at the detriment of the other, it means that the result will change but always along the straight line, if the parameters changed are related to thermoeconomic. When the steam consumption of the process is changed, thermodynamic parameters will also be changed, so the costs of the final products will not follow the straight line, in fact, a new line will be created. thus, each case will have its own solution straight line.

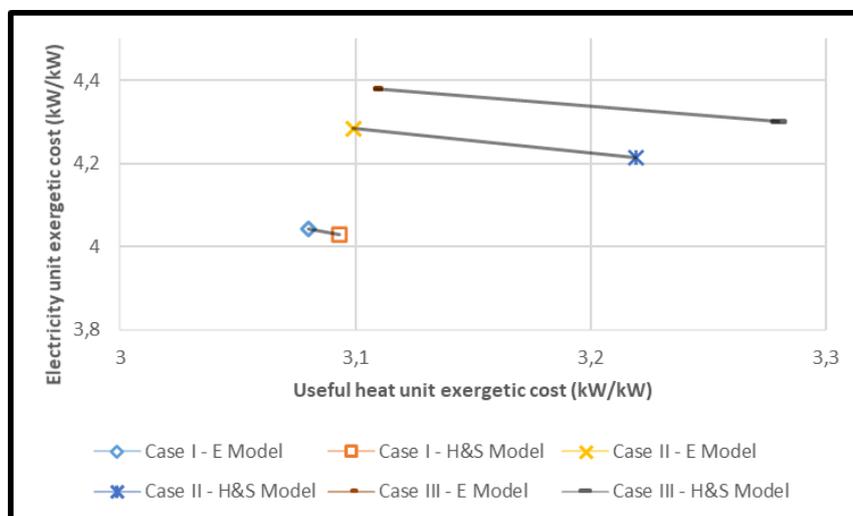


Figure 4. Unit Exergetic Cost – Straight line solution.

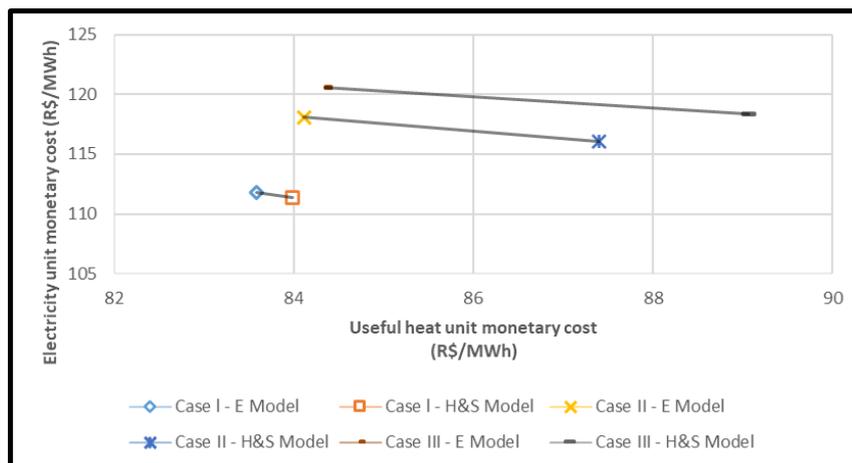


Figure 5. Unit Monetary Cost – Straight line solution.

It can be seen, still in Figures 4 and 5, with the increase of steam consumption by the process the results of the models get closer, tending to be equal when all the steam produced by the plant is destined to the process indicating the production of useful heat only.

4. CONCLUSIONS

The thermal integration presents significant reductions in process steam consumption, since it achieves the same production of sugar and alcohol with less steam, in addition to expanding the electricity surplus, but the thermoeconomic evaluation shows higher costs when increasing the level of integration. The change of costs in the thermoeconomic comes from the difference of the models, with the cost of one product increasing in detriment of other, where the costs will always be in the solution straight line. In the results obtained this does not happen, because when the process steam consumption changes, thermodynamic parameters are influenced, revealing the reason why the new costs do not respect the existing solution straight line, but will generate new straight lines. The higher costs can also be justified with the by-pass line, because its flow rate increases when the integration level is improved, due to the output temperature of the deaerator being fixed, with higher integration level more steam will be condensed, therefore, more saturated steam is needed to keep this operational parameter constant, thus, the by-pass line steals part of the exergy that would be destined to the turbine. Another contribution to the cost increase is related to the conversion of exergy into electricity in the turbine and generator, as with increasing integration level a more amount of steam will be sent to these equipments, causing higher irreversibilities and also justifying the lower exergetic efficiency. It is also possible conclude that the results presented by the different thermoeconomic models will be equal at the point that corresponds to the highest steam consumption, where all the exergy produced in the plant will be consumed by the process, with no cogeneration.

The thermoeconomic analysis shows great capacity to relate the final products with the inputs of a cogeneration system and thermal integration, despite presenting higher costs, promotes an increase in process efficiency, which confirms the potential for improvement and reinforces the importance of exploring new methods for optimizing steam utilization.

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