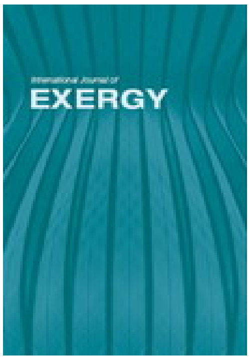

International Journal of Exergy

ISSN online: 1742-8300 - ISSN print: 1742-8297
https://www.inderscience.com/ijex

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DOI: 10.1504/IJEX.2023.10053570

Article History:

Received:	05 December 2021
Last revised:	08 April 2022
Accepted:	30 April 2022
Published online:	25 January 2023

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Abstract: The increase in industrial needs increased the demand for fuels, electricity and the growth of climatic effects. This study performs an exergoeconomic evaluation in a sugar, ethanol and electricity production plant located in the Northeast of Brazil. The objective is to identify thermoeconomic inefficiencies, exergy destruction and efficiencies, determine the costs of exergy flows and a step by step of exergoeconomic diagnosis using the SPECO method. The results show the greatest inefficiencies presented in boiler 1 (48 MW, 28%), boiler 2 (43 MW, 25%) and boiler 3 (31 MW, 18%). The production of steam costs R$63.88 for each GJ of energy. The total cost of exergy destruction in the boilers is R$3,808 per hour of operation which means about 84% of all exergy destroyed in the plant. The exergoeconomic diagnosis concludes that the equipment that needs optimisation primarily is the deaerator (5,904% rk) and the condenser (1,674% rk).

Keywords: exergoeconomic; exergy destruction; specific exergy cost; SPECO; sugar cane; thermodynamic analysis.

Reference to this paper should be made as follows: da Silva Jr., E.J., Silva Santos, C.M., de Oliveira Porangaba, M.A., de Oliveira, R.A. and da Silva Marques, A. (2023) 'Exergetic assessment and exergoeconomic diagnosis of a sugarcane plant in northeastern Brazil', *Int. J. Exergy*, Vol. 40, No. 1, pp.15–33.

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This paper is a revised and expanded version of a paper entitled 'Exergetic assessment for exergoenvironmental diagnosis of a sugarcane plant in northeastern of Brazil' presented at 9th Global Conference on Global Warming, Virtual, Croatia, 1–4 August 2021.

1 Introduction

There is common sense in the world that energy resources are finite and policies against energy waste need to be taken (Martinez et al., 2017; Nascimento and Alves, 2016). In this way, science has great importance and clarifying purpose in the application of concepts and theories like thermodynamics laws.

Renewable energy sources, such as biomass, contribute to the supply of energy in a consistent perennial manner and have a less environmental impact than fossil fuels (Kim and Yoon, 2016). According to the National Energy Balance (EPE, 2019), sugarcane biomass in Brazil corresponds to 18% of the internal energy supply within the energy matrix.

The laws of thermodynamics have proved to be important tools for evaluating and pointing out the need for optimisation in industrial energy systems (Sheykhi, 2019; Burke and Stephens, 2018). Exergy is the property that quantifies the potential for energy use (Moran et al., 2015). The exergy analysis gives the possibility to identify the equipment that most destroys exergy and thus determine the priorities for improvements.

Meanwhile, the term 'thermoeconomics' is defined by Bejan et al. (1996) as the branch of engineering which combines exergy analysis with economic principles to present global monetary results of processes and equipment. This kind of analysis determines results like cost per energy unit and cost per time unit.

Different methods have been used in thermoeconomic evaluations. One of them is the specific exergy cost (SPECO) method, which is defined by Lazaretto and Tsatsaronis (2006b) as the specific exergy costing. It is characterised by the principle of inputs and fuels for the evaluation of the exergetic flows of a system. Allied to this, there is the application of cost equations and business management concepts to provide diagnostics of financial losses.

For instance, in the work presented by Díaz et al. (2018), a thermoeconomic analysis of a cogeneration system in an alcohol producing plant in Brazil was performed. It showed that steam reheating in different scenarios resulted in increased energy efficiency and leftover sugarcane bagasse. This allowed the estimation of the potential for energy production in off-season periods and the destination of the spare bagasse for the production of second-generation alcohol production (Hiloidhari et al., 2021).

In the paper presented by Marques et al. (2020), an application of the SPECO method to a micro-trigeneration power unit can be seen. It is a specific configuration, consisting of an internal combustion engine, an absorption refrigeration system and a heat recovery unit to meet the demands of a university building in northeastern Brazil. The thermoeconomic evaluation has allowed identifying the equipment which would get the benefit from the optimisation of the system. The results demonstrate that the priority for improvement should be on the combustion engine followed by the steam generator of the absorption system.

The results of Amid et al. (2021) demonstrate the efficiency of applying energy and economic analysis by the SPECO method in an industrial plant to produce alcohol from sugarcane molasses. The study compares the energy and environmental efficiency to produce electricity by using diesel, gasoline, or natural gas as fuel. The results show that the best configuration is when using natural gas. This can be an important recommendation for the plant evaluated in this paper.

In this context, the present work deals with the thermoeconomic evaluation of a sugarcane plant, located in the northeast region of Brazil, under different conditions of harvest and time. This is a particular and unique study where the following contributions and innovative aspects can be highlighted:

1 This is a step by step thermodynamic and exergoeconomic evaluation routine, which will help other researchers to reproduce this type of study in other specific applications.

2 The evaluation was carried out in a specific sugar, alcohol and electricity production real plant located in a small city of northeastern Brazil.

3 A complete study of the combustion of the burning of sugarcane bagasse produced in that region was presented.

2 Sugar plant description

The evaluation was carried out in a sugar, alcohol and electricity production plant located in the state of Pernambuco, which is located in the northeast region of Brazil. The system consists of three boilers that operate in parallel, a set of seven steam turbines for generating electricity and driving machines and equipment for the production processes, a desuperheater, a condenser, a deaerator, and two hydraulic pumps.

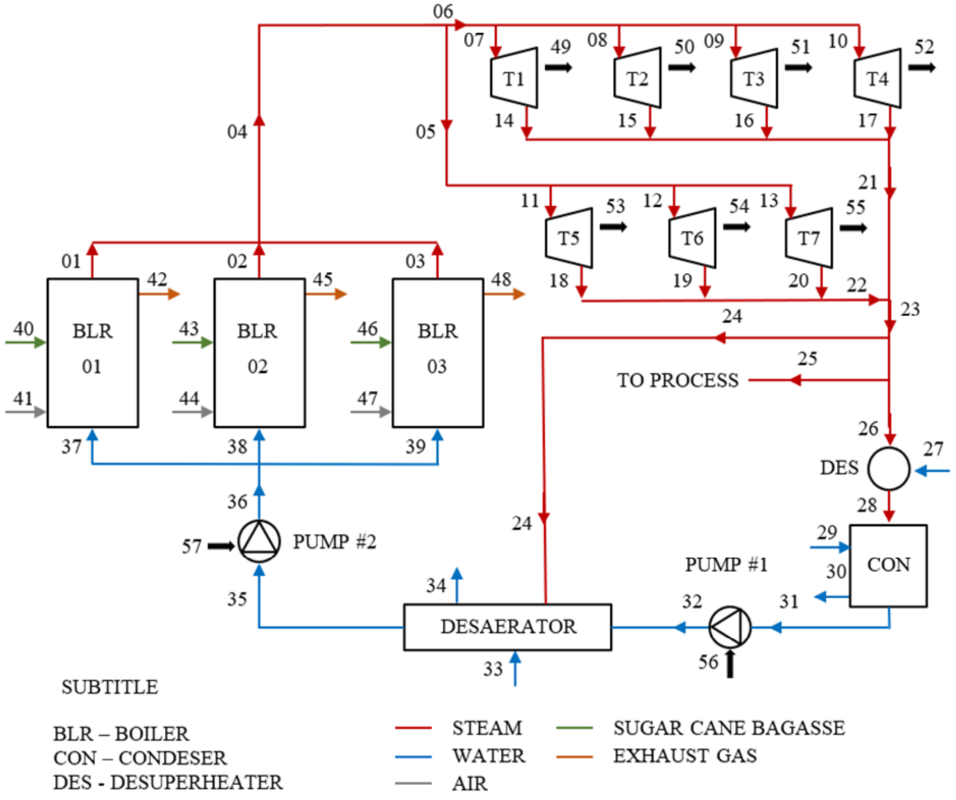
The plant can generate 11.8 MWh of electricity from the burning of sugarcane bagasse in the boilers that generate steam to feed the turbines. The diagram of Figure 1 represents the plant with its equipment and the 57 energy flows evaluated.

The process starts with the entry of sugarcane bagasse and preheated ambient air (flows #40, #41, #43, #44, #46 and #47) into each boiler. These boilers are of the water-tube type, that is, the water and steam are contained inside the tubes, while the hot combustion gases are in contact with the tubes externally. Streams 42, 45 and 48 represent the exit of the exhaust gases through the chimneys of the boilers after undergoing particulate separation treatment. The thermal energy from combustion is transferred to the water through the boiler's tubes, producing superheated steam for flows #1, #2 and #3. The steam from stream #6 feeds backpressure turbines T1, T2, T3 and T4 used in the production of electricity. The electricity produced is destined to supply the demands of the industry itself and the surplus energy is sold by the local energy concessionaire. Steam flow #5 feeds the T5, T6 and T7 turbines, responsible for activating the equipment of the production process: one sugarcane shredder, three milling suits and one pump to feed water to the boilers.

Flow #23 represents the low-pressure steam extracted from the turbines. Part of this steam goes to the deaerator through flow #24 to reduce the levels of insoluble gases in the water that feeds the boilers. Another part of the low-pressure steam is used in the distillery for ethanol production (flow #25). The remaining steam (flow #26) passes through the desuperheater to reduce the temperature of the steam before it reaches the condenser. Stream #27 represents the addition of cold water to the steam to complete the desuperheating process.

Steam of flow #28 is the 'low-quality' steam that goes to the condenser, which is cooled by the low temperatures (flow #29). The water is pumped (flow #32) to the deaerator, where elements like oxygen are removed to avoid erosion in the tubes and parts of the boilers. Flow #33 represents the make-up water for the process because during the cycle operation it is common for water and steam to be lost to the environment during the plant's production process. Stream 36 is the water pumped back to the boilers, restarting the cycle.

Figure 1 Sugarcane plant diagram (see online version for colours)



3 Thermodynamic modelling

One of the important premises of this work was to have a representative model of a production process in a sugar and ethanol industry. Thereby, thermodynamic properties were collected at the different times of the day: 0:00 h, 6:00 h, 12:00 h, and 18:00 h along 163 days of the harvest period of the 2019–2020 biennium, which started with milling in September 2019 and ended in February 2020. The daily and monthly arithmetic mean of the collected data was performed. For the variations of the data obtained, the scenario of best repeatability and reliability of the process information was established.

A mathematical model was developed in this study to simulate different operating conditions of the plant. The code was developed in the Engineering Equation Solver (EES) platform to perform the thermodynamic and exergoeconomic modelling, and thus obtain the thermal and economic efficiency analysis and diagnostics.

Table 1 Application of balance equations for each equipment of the production plant

Equipment	*Mass conservation*	*Energy conservation*	*Exergy balance*	*Irreversibility*
Boiler #1	$\dot{m}_{01} = \dot{m}_{37}$ $\dot{m}_{40} + \dot{m}_{41} = \dot{m}_{42}$	$\dot{Q}_{B\#1} = \dot{m}_{01}(h_{37} - h_{01})$ $\dot{Q}_{fuel,B\#1} = n_{42}h_{42} - n_{40}h_{40} - n_{41}h_{41}$	$\Delta\dot{E}x_{B\#1} = (\dot{m}_{40}ex_{40} + \dot{m}_{41}ex_{41} - \dot{m}_{42}ex_{42})$ $-\dot{m}_{01}(ex_{37} - ex_{01})$	$\dot{I}_{B\#1} = (\dot{E}x_{40} + \dot{E}x_{41} - \dot{E}x_{42})$ $-(\dot{E}x_{37} - \dot{E}x_{01})$
Boiler #2	$\dot{m}_{02} = \dot{m}_{38}$ $\dot{m}_{43} + \dot{m}_{44} = \dot{m}_{45}$	$\dot{Q}_{B\#2} = \dot{m}_{02}(h_{38} - h_{02})$ $\dot{Q}_{fuel,B\#2} = n_{45}h_{45} - n_{43}h_{43} - n_{44}h_{44}$	$\Delta\dot{E}x_{B\#2} = (\dot{m}_{43}ex_{43} + \dot{m}_{44}ex_{44} - \dot{m}_{45}ex_{45})$ $-\dot{m}_{02}(ex_{38} - ex_{02})$	$\dot{I}_{B\#2} = (\dot{E}x_{43} + \dot{E}x_{44} - \dot{E}x_{45})$ $-(\dot{E}x_{38} - \dot{E}x_{02})$
Boiler #3	$\dot{m}_{03} = \dot{m}_{39}$ $\dot{m}_{46} + \dot{m}_{47} = \dot{m}_{48}$	$\dot{Q}_{B\#3} = \dot{m}_{03}(h_{39} - h_{03})$ $\dot{Q}_{fuel,B\#3} = n_{48}h_{48} - n_{46}h_{46} - n_{47}h_{47}$	$\Delta\dot{E}x_{B\#3} = (\dot{m}_{46}ex_{46} + \dot{m}_{47}ex_{47} - \dot{m}_{48}ex_{48})$ $-\dot{m}_{03}(ex_{39} - ex_{03})$	$\dot{I}_{B\#3} = (\dot{E}x_{46} + \dot{E}x_{47} - \dot{E}x_{48})$ $-(\dot{E}x_{39} - \dot{E}x_{03})$
Turbine #1	$\dot{m}_{07} = \dot{m}_{14}$	$\dot{W}_{49} = \dot{m}_{07}(h_{07} - h_{14})$	$\Delta\dot{E}x_{T\#1} = \dot{W}_{49} + \dot{m}_{07}(ex_{07} - ex_{14})$	$\dot{I}_{T\#1} = T_0\dot{m}_{07}(s_{14} - s_{07})$
Turbine #2	$\dot{m}_{08} = \dot{m}_{15}$	$\dot{W}_{50} = \dot{m}_{08}(h_{08} - h_{15})$	$\Delta\dot{E}x_{T\#2} = \dot{W}_{50} + \dot{m}_{08}(ex_{08} - ex_{15})$	$\dot{I}_{T\#2} = T_0\dot{m}_{08}(s_{14} - s_{08})$
Turbine #3	$\dot{m}_{09} = \dot{m}_{16}$	$\dot{W}_{51} = \dot{m}_{09}(h_{09} - h_{16})$	$\Delta\dot{E}x_{T\#3} = \dot{W}_{51} + \dot{m}_{09}(ex_{09} - ex_{16})$	$\dot{I}_{T\#3} = T_0\dot{m}_{09}(s_{16} - s_{09})$
Turbine #4	$\dot{m}_{10} = \dot{m}_{17}$	$\dot{W}_{52} = \dot{m}_{10}(h_{10} - h_{17})$	$\Delta\dot{E}x_{T\#4} = \dot{W}_{52} + \dot{m}_{10}(ex_{10} - ex_{17})$	$\dot{I}_{T\#4} = T_0\dot{m}_{10}(s_{17} - s_{10})$
Turbine #5	$\dot{m}_{11} = \dot{m}_{18}$	$\dot{W}_{53} = \dot{m}_{11}(h_{11} - h_{18})$	$\Delta\dot{E}x_{T\#5} = \dot{W}_{53} + \dot{m}_{11}(ex_{11} - ex_{18})$	$\dot{I}_{T\#5} = T_0\dot{m}_{11}(s_{18} - s_{11})$
Turbine #6	$\dot{m}_{12} = \dot{m}_{19}$	$\dot{W}_{54} = \dot{m}_{12}(h_{12} - h_{19})$	$\Delta\dot{E}x_{T\#6} = \dot{W}_{54} + \dot{m}_{12}(ex_{12} - ex_{19})$	$\dot{I}_{T\#6} = T_0\dot{m}_{12}(s_{19} - s_{12})$
Turbine #7	$\dot{m}_{13} = \dot{m}_{20}$	$\dot{W}_{55} = \dot{m}_{13}(h_{13} - h_{20})$	$\Delta\dot{E}x_{T\#7} = \dot{W}_{55} + \dot{m}_{13}(ex_{13} - ex_{20})$	$\dot{I}_{T\#7} = T_0\dot{m}_{13}(s_{20} - s_{13})$
Desuperheater	$\dot{m}_{26} + \dot{m}_{27} = \dot{m}_{28}$	$\dot{m}_{26}h_{26} + \dot{m}_{27}h_{27} = \dot{m}_{28}h_{28}$	$\Delta\dot{E}x_{des} = \dot{m}_{26}ex_{26} + \dot{m}_{27}ex_{27} - \dot{m}_{28}ex_{28}$	$\dot{I}_{des} = \dot{E}x_{26} + \dot{E}x_{27} - \dot{E}x_{28}$
Condenser	$\dot{m}_{28} = \dot{m}_{31}$ $\dot{m}_{29} = \dot{m}_{30}$	$\dot{Q}_C = \dot{m}_{28}(h_{28} - h_{31})$	$\Delta\dot{E}x_C = \dot{m}_{28}ex_{28} + \dot{m}_{29}ex_{29}$ $-\dot{m}_{30}ex_{30} - \dot{m}_{31}ex_{31}$	
Pump 1	$\dot{m}_{31} = \dot{m}_{32}$	$\dot{W}_{56} = \dot{m}_{31}(h_{32} - h_{31})$	$\Delta\dot{E}x_{p\#1} = \dot{W}_{56} + \dot{m}_{31}(ex_{31} - ex_{32})$	$\dot{I}_{P\#1} = T_0\dot{m}_{31}(ex_{32} - ex_{31})$
Deaerator	$\dot{m}_{35} + \dot{m}_{34} = \dot{m}_{24} + \dot{m}_{32} + \dot{m}_{33}$	$\dot{m}_{35}h_{35} + \dot{m}_{34}h_{34} = \dot{m}_{24}h_{24} + \dot{m}_{32}h_{32}$ $+\dot{m}_{33}h_{33}$	$\Delta\dot{E}x_{Dea} = \dot{m}_{24}ex_{24} + \dot{m}_{32}ex_{32} + \dot{m}_{33}ex_{33}$ $-\dot{m}_{34}ex_{34} - \dot{m}_{35}ex_{35}$	$\dot{I}_{Dea} = \dot{E}x_{24} + \dot{E}x_{32} + \dot{E}x_{33}$ $-\dot{E}x_{34} - \dot{E}x_{35}$
Pump 2	$\dot{m}_{35} = \dot{m}_{36}$	$\dot{W}_{57} = \dot{m}_{35}(h_{36} - h_{35})$	$\Delta\dot{E}x_{p\#2} = \dot{W}_{57} + \dot{m}_{35}(ex_{35} - ex_{36})$	$\dot{I}_{P\#2} = T_0\dot{m}_{36}(ex_{36} - ex_{35})$

The analysis begins by obtaining the thermodynamic properties of each stream in the production plant. Then, the mass flows, energy and exergy are obtained by conservation and balancing equations. The following assumptions were considered for the development of this analysis:

1 the environmental reference state: pressure of 101.3 kPa and temperature of 25°C
2 air and combustion products are ideal gas mixtures
3 complete combustion of the reactants
4 the steam expansion in the turbines and water compression in the pumps are adiabatic processes
5 steady-state processes
6 kinetic energy and power effects are neglected.

From these assumptions, the conservation and balance equations were simplified to the conservation of mass [equation (1)], conservation of energy [equation (2)] and exergy balance [equations (3), (4) and (5)]. Applying these equations for each component, we have the set of equations shown in Table 1 which are based on the flows shown in Figure 1.

$$\sum \dot{m}_i = \sum \dot{m}_o \tag{1}$$

$$0 = \dot{Q} + \dot{Q} + \sum \dot{m}_i h_i - \sum \dot{m}_o h_o \tag{2}$$

$$\Delta \dot{E}x = \dot{W} + \sum \dot{m}_i ex_i - \sum \dot{m}_o ex_o \tag{3}$$

$$ex = (h - h_0) - T_0 (s - s_0) \tag{4}$$

$$\sum \dot{m}_i ex_i + \sum \left(1 - \frac{T_0}{T_r}\right) \dot{Q}_r = \sum \dot{m}_o ex_o + \dot{W} + \dot{I} \tag{5}$$

Equation (6) was used to determine the energy of the sugarcane bagasse combustion process, following what is established in Moran et al. (2015).

$$\dot{Q} + \sum n_i h_R = \sum n_e h_p + \dot{W} \tag{6}$$

Enthalpy is obtained separately for reagents and products, using equation (7) which deals with forming enthalpy.

$$h = \overline{h}_f^0 + \Delta \overline{h} \tag{7}$$

Table 1 shows the resulting equations for mass balance, energy balance, exergetic balance and irreversibilities for each of the evaluated equipment.

The energy analysis of the boilers begins with the calculation of the combustion process of sugarcane biomass that takes place inside the furnaces. The elements contained in the bagasse are: C is 24.32%, H_2 is 2.935%, S is 0.02%, N_2 is 0.08%, O_2 is 21.425%, $H_2O(l)$ 50%, and ash is 1.22% (Cavalcanti et al., 2020). The air present in the mixture is composed of 21% O_2 and 79% N_2. Based on this idealisation, the molar ratio of nitrogen to oxygen is 3.76 (Moran et al., 2015). Therefore, equation (8) represents the stoichiometric chemical equation of the sugarcane bagasse combustion process. The fractions of each element refer to the percentage on a molar basis. The balancing of the equation allows finding the molar fractions for the elements of the combustion gases, represented by the coefficients $\alpha_{\#}$. In this work, the combustion process was evaluated with 30% excess air.

$$\begin{aligned}&\left[0.2794.C + 0.2007.H_2 + 0.09271.O_2 + 0.00107.N_2 + 0.00002337.S\right.\\&\left.+0.4159.H_2O_{(l)} + 0.01021.ash\right] + \varphi_{ar}.x.\left[O_2 + 3.76N_2\right] \rightarrow \alpha_1.CO_2 + \alpha_2.H_2O\\&+\alpha_3.O_2 + \alpha_4.N_2 + \alpha_5.SO_2 + \alpha_6.ash\end{aligned} \tag{8}$$

The energy and exergy efficiency of boilers are defined by equation (9) and equation (10), respectively (Rein, 2012):

$$\eta_B = 100.\frac{\dot{m}_{steam}\left(h_{steam} - h_w\right)}{\dot{m}_{fuel}PCI} \tag{9}$$

$$\varepsilon_B = 100.\frac{\left(\dot{E}x_{steam} - \dot{E}x_w\right)}{\dot{E}x_{fuel} + \dot{E}x_{air} - \dot{E}x_{gas}} \tag{10}$$

The chemical exergy of the fuel was determined by equation (11), and the chemical exergy of substances (β) is determined by equation (12) according to Szargut et al. (1988).

$$ex_{fuel} = \beta.\left(PCI_0 + \dot{W}.h_{lv}\right) + 9682.S + ex_{ash} + ex_w.\dot{W} \tag{11}$$

$$\beta = \frac{\left(1.044 + 0.0160.\frac{H}{C} - 0.3493.\frac{O}{C}.\left(1 + 0.0531.\frac{H}{C}\right) + 0.0493.\frac{N}{C}\right)}{\left(1 - 0.4124.\frac{O}{C}\right)} \tag{12}$$

The total exergy of the intake air is defined by equation (13), which requires the calculation of chemical exergy and physical exergy, given by equations (14) and (15), respectively:

$$ex_{total_{air}} = ex_{ph_{air}} + ex_{ch_{air}} \tag{13}$$

$$ex_{ph_{air}} = \left(h_{air} - h_{0_{air}}\right) - T_0.\left(s_{air} - s_{0_{air}}\right) \tag{14}$$

$$ex_{ch_{air}} = x_{iO_2}.ex_{chiO_2} + x_{iN_2}.ex_{chiN_2} + R.T_0.\left(x_{iO_2}.\ln\left(x_{iO_2}\right) + x_{iN_2}.\ln\left(x_{iN_2}\right)\right) \tag{15}$$

The chemical exergy for combustion gases is determined by equation (16).

$$ex_{ch_{EG}} = \sum_i y_i.ex_{ch}^0 + R.T_0.\left(\sum_i y_i.\ln\left(y_i\right)\right) \tag{16}$$

The temperature, pressure, flow and power values of the plant's equipment were obtained from the manufacturers' catalogues as shown in Table 2. It was assumed 98% of mechanical efficiency for the steam turbines and 97% efficiency for the electric power generator (Rein, 2012).

Table 2 Input data of boilers, turbines and pumps

Equipment	*Manufacturer*	*Specific consumption (kg_{bag}/kg_{stem})*	T_i *(°C)*	P_i *(MPa)*	T_o *(°C)*	P_o *(MPa)*	$\dot{m}\left[\frac{kg}{s}\right]$
Boiler #1	C.B. Serv.	0.45	---	---	320	0.21	22.22
Boiler #2	DZ SA	0.45	---	---	300	0.21	18.33
Boiler #3	ZANINI	0.45	---	---	350	0.21	15.28
Turbine #1	Dresser-Rand	---	320	2.10	130	0.02	6.56
Turbine #2	Dresser-Rand	---	320	2.10	160	0.02	6.72
Turbine #3	Dresser-Rand	---	320	2.10	130	0.02	15.28
Turbine #4	Worthington	---	320	2.10	135	0.02	4.89
Turbine #5	Dedini	---	320	2.10	180	0.02	1.66
Turbine #6	Turbimaq	---	300	2.10	180	0.02	3.37
Turbine #7	Texas	---	320	2.10	180	0.02	2.44
Pump #1	Team	---	90	0.09	91	0.02	36.11
Pump #2	Team	---	97	0.14	97	0.25	41.67

The efficiencies of the first law, isentropic analysis and exergy for the turbines are defined by equations (17), (18) and (19), respectively:

$$\eta_T = 100.\frac{\dot{W}}{\dot{m}_{steam}\left(h_i - h_o\right)} \tag{17}$$

$$\eta_{T,Iso} = 100.\frac{\dot{W}}{\dot{m}_{steam}\left(h_i - h_{o,Iso}\right)} \tag{18}$$

$$\eta_{T,Ex} = 100.\frac{\dot{W}}{\dot{m}_{steam}\left(ex_i - ex_o\right)} \tag{19}$$

The efficiencies for the pumps are calculated by equations (20), (21) and (22):

$$\eta_P = 100.\frac{\dot{m}_{steam}\left(h_i - h_o\right)}{\dot{W}} \tag{20}$$

$$\eta_{P,Iso} = 100.\frac{\dot{m}_{steam}\left(h_i - h_{o,Iso}\right)}{\dot{W}} \tag{21}$$

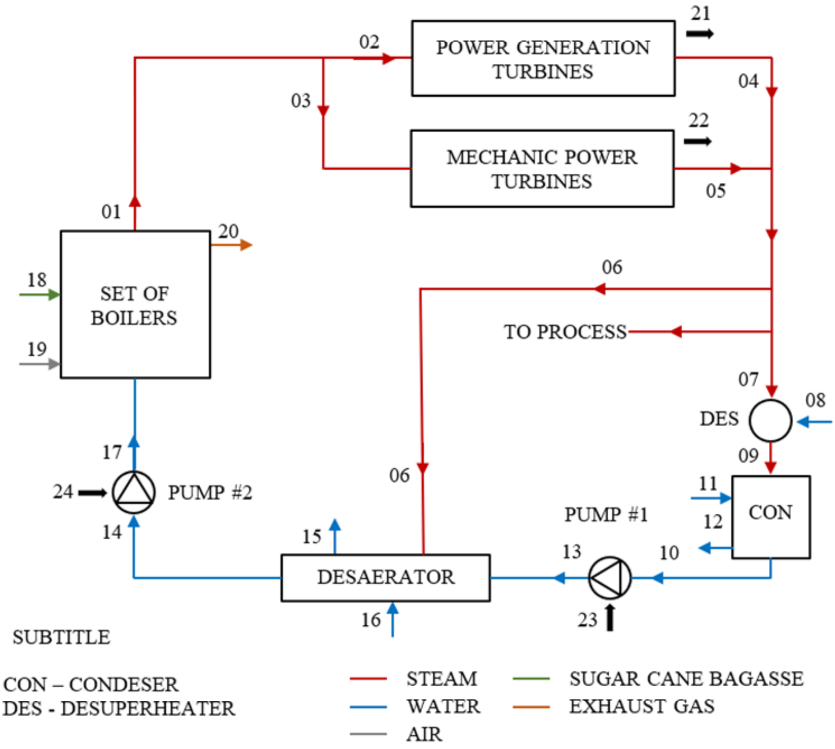
$$\eta_{B,Ex} = 100.\frac{\dot{m}_{steam}\left(ex_i - ex_o\right)}{\dot{W}}. \tag{22}$$

4 Exergoeconomic modelling

The exergoeconomic analysis combines the concepts of exergy and economic engineering to evaluate and improve the performance of energy systems, projecting the optimal scenario in terms of costs and the values of thermodynamic inefficiencies in each component (Tsatsaronis and Ho-Park, 2002). In this sense, the exergoeconomic method adopted in this study is SPECO, by Lazaretto and Tsatsaronis (2006b), which associates the values of exergy flows with monetary values, from the definition of products and fuels applied to each control volume.

Figure 2 represents the industrial processes that were evaluated by the exergoeconomic analysis. The three boilers were represented in a single control volume and the same was done for the set of power generation turbines and for the turbines that meet the mechanical demands of the plant.

Figure 2 Plant diagram for the exergoeconomic evaluation (see online version for colours)



The set of equations (23) to (26) are used to determine the cost rates in each equipment, associated with energy inputs and outputs (Meyer et al., 2009; Lazaretto and Tsatsaronis, 2006a).

$$\dot{C}_i = c_i \dot{E}x_i = c_i \dot{m}_i ex_i \tag{23}$$

$$\dot{C}_P = c_w \dot{W} \tag{24}$$

$$\dot{C}_Q = c_Q \dot{E}x_Q \tag{25}$$

The cost balance was developed from equation (26) which is presented in Bejan (1996):

$$\sum \left(c_o \dot{E}x_o\right)_k + \left(c_w \dot{W}\right)_k = \sum \left(c_i \dot{E}x_i\right)_k + \left(c_Q \dot{E}x_Q\right)_k + \dot{Z}_k \tag{26}$$

The total cost rate of equipment in the system is defined by equation (27) and the capital recovery factor *CRF* by equation (28).

$$\dot{Z}_k = Z_k.CRF.\varphi \tag{27}$$

$$CRF = i\frac{(1+i)^{n_y}}{(1+i)^{n_y-1}} \tag{28}$$

A peculiar characteristic of the SPECO method is the need for auxiliary equations to close the linear equations system, once, there are more flows than the amount of equipment in the system. This is done by the *F* and *P* principles. Principle *F* says that the specific cost associated with the exergy removed from the fuel must be equal to the average specific cost at which the exergy removed was supplied to the same stream of the next piece of equipment. The *P* principle says that each unit of exergy is supplied to any stream associated with the product at the same average cost (Lazaretto and Tsatsaronis, 2006b).

Equations (29) to (32) describe the exergy destruction, the average cost of products and fuels, and the cost rate of exergy destruction, respectively:

$$\dot{Ex}_{D,k} = \dot{Ex}_{P,k} - \dot{Ex}_{F,k} \tag{29}$$

$$C_{P,k} = \frac{\dot{C}_{P,k}}{\dot{Ex}_{P,k}} \tag{30}$$

$$C_{F,k} = \frac{\dot{C}_{F,k}}{\dot{Ex}_{F,k}} \tag{31}$$

$$\dot{C}_{D,k} = c_{F,k}.\dot{Ex}_{D,k} \tag{32}$$

Equations (33) and (34) represent the two important parameters to find by the application of the SPECO. They are the relative cost and the exergy factor, respectively:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{33}$$

$$f_k = \left(\frac{\dot{Z}_k}{C_{D,k} + Z_k}\right).100 \tag{34}$$

The cost rates of the fuels (bagasse, water and electricity) are determined by equations (35) to (37):

$$\dot{C}_{fuel} = \frac{\dot{m}_{fuel}}{\rho_{fuel}} = \$_{fuel} \tag{35}$$

$$\dot{C}_w = \frac{\dot{m}_w}{\rho_w}\$_w \tag{36}$$

$$\dot{C}_{ee} = \frac{\dot{m}_{ee}}{\rho_{ee}}\$_{ee} \tag{37}$$

Table 3 presents the input data for the exergoeconomic assessment and how they were obtained.

Table 3 Input data for the exergoeconomic evaluation

Symbol	*Description*	*Value*	*Unit*
$\$_{fuel}$	Fuel cost	100.00	R$/ton
$\$_{ee}$	Cost of electricity	0.37	R$/kWh
$\$_{air}$	Air cost	0.00	R$/m^3
$\$_{w}$	Water cost	1.10	R$/m^3
Z_B	Boiler acquisition cost	30,000,000.00	R$
Z_{gen}	Generator acquisition cost	7,500,000.00	R$
Z_{TD}	Turbo-drive acquisition cost	2,500,000.00	R$
Z_{des}	Desuperheater acquisition cost	30,000.00	R$
Z_{COND}	Condenser acquisition cost	750,000.00	R$
$Z_{P\#1}$	Pump #1 acquisition cost	50,000.00	R$
Z_D	Deaerator acquisition cost	150,000.00	R$
$Z_{P\#2}$	Pump #2 acquisition cost	150,000.00	R$
i	Annual interest rate	6.00	%
n_Y	Equipment lifetime	25	Years
n_h	Operation hours per year	3,888.00	h/year
φ	Equipment maintenance factor	6.00	%

5 Results and discussion

The chemical equation resulting from the complete combustion of bagasse with 30% excess air is:

$$\begin{aligned}&\left[0.2794.C+0.2007.H_2+0.09271.O_2+0.00107.N_2+0.00002337.S\right.\\&\left.+0.4159.H_2O_{(l)}+0.01021.ash\right]+1.3.0.2871.\left[O_2+3.76.N_2\right]\rightarrow 0.2794.CO_2\\&+0.6166.H_2O_{(g)}+0.0862.O_2+0.1414.N_2+0.00002337.SO_2+0.0102.ash\end{aligned}$$

Table 4 Results of thermodynamic analysis of combustion process in the boilers

Parameter	*Value*	*Unit*	*Description*
$\dot{Q}_{fuel}$	231	MW	Inlet energy by fuel
$\dot{Q}_{EG}$	99	MW	Heat loss by exhaust gases
$\dot{E}x_{fuel}$	199	MW	Fuel exergy
$\dot{E}x_{EG}$	39	MW	Exergy combustion products
η_B	82.69	%	Boiler energy efficiency
ε_B	25.55	%	Boiler exergetic efficiency

Table 5 Thermodynamic states and exergy results

#	*T (°C)*	$\dot{m}$ *(kg/s)*	*P (kPa)*	*x (%)*	*s (kJ/kgK)*	*ex (kJ/kg)*	*Ex (MW)*	#	*T (°C)*	$\dot{m}$ *(kg/s)*	*P (kPa)*	*x (%)*	*s (kJ/kgK)*	*ex (kJ/kg)*	*Ex (MW)*
1	339	16.30	2,039	100	6.907	1,057	17.23	30	110	47.20	150	0	1.419	42.95	2.03
2	327	14.66	2,039	100	6.861	1,043	15.29	31	90	33.36	105	0	1.193	25.97	0.87
3	308	9.87	2,039	100	6.787	1,021	10.08	32	90	33.36	120	0	1.195	26.15	0.87
4	333	40.83	2,039	100	6.883	1,050	42.85	33	25	6.15	120	0	0.367	0.02	0.00
5	333	7.38	2,039	100	6.883	1,050	7.75	34	99	0.10	101	0	1.296	33.13	0.03
6	333	33.45	2,039	100	6.883	1,050	35.11	35	99	40.83	135	0	1.296	33.16	1.35
7	333	6.56	2,039	100	6.883	1,050	6.89	36	100	40.83	2,500	0	1.308	36.53	1.49
8	333	6.72	2,039	100	6.883	1,050	7.05	37	140	16.30	2,500	0	1.737	77.26	1.26
9	333	15.28	2,039	100	6.883	1,050	16.04	38	140	14.66	2,500	0	1.737	77.26	1.13
10	333	4.89	2,039	100	6.883	1,050	5.13	39	140	9.87	2,500	0	1.737	77.26	0.76
11	333	2.12	2,039	100	6.883	1,050	2.23	40	25	7.01	101	---	---	11,331.00	79.42
12	333	2.86	2,039	100	6.883	1,050	3.00	41	130	24.32	101	---	---	19.64	0.48
13	333	2.40	2,039	100	6.883	1,050	2.52	42	300	31.33	101	---	---	491.60	3.45
14	171	6.56	105	100	7.687	530	3.47	43	25	6.30	101	---	---	11,331.00	71.43
15	173	6.72	105	100	7.695	531	3.57	44	130	21.87	101	---	---	19.64	0.43
16	181	15.28	105	100	7.732	536	8.20	45	300	28.18	101	---	---	491.60	3.10
17	183	4.89	105	100	7.740	538	2.63	46	25	4.24	101	---	---	11,331.00	48.09
18	245	2.12	105	100	7.992	585	1.24	47	130	14.73	101	---	---	19.67	0.29
19	141	2.86	105	100	7.550	512	1.46	48	300	18.97	101	---	---	491.60	2.09
20	159	2.40	105	100	7.635	522	1.25	49	---	---	---	---	---	---	1.84
21	178	33.45	105	100	7.717	534	17.86	50	---	---	---	---	---	---	1.86
22	177	7.38	105	100	7.713	533	3.94	51	---	---	---	---	---	---	3.97
23	177	40.83	105	100	7.716	534	21.80	52	---	---	---	---	---	---	1.25
24	177	1.32	105	100	7.716	534	0.70	53	---	---	---	---	---	---	0.28
25	177	7.30	105	100	7.716	534	3.90	54	---	---	---	---	---	---	0.97
26	177	32.21	105	100	7.716	534	17.20	55	---	---	---	---	---	---	0.73
27	25	1.15	120	0	0.367	0.02	0.00	56	---	---	---	---	---	---	0.03
28	130	33.36	105	100	7.496	505.6	16.87	57	---	---	---	---	---	---	0.28
29	90	47.20	170	0	1.192	26.04	1.23								

The products of sugarcane bagasse combustion, for this modelling, were about: 28% CO_2, 62% H_2O, 9% O_2, 14% N_2, minimum of SO_2 and ash.

Table 4 presents the results of energy rates, exergy rates and efficiencies of the boilers where the bagasse combustion process takes place. Note that exergy rates are lower than energy rates since exergy deals with the useful work that is effectively used in the process. While the efficiency of the 1st law of thermodynamics was close to 83%, the efficiency of the second law was around 26%, leading to the conclusion that there are energy losses that must be minimised to maximise the use and efficiency of the boiler. Part of this loss is due to the destruction of exergy during the chemical reaction of combustion, another part is due to the moisture contained in the sugarcane bagasse.

The results of thermodynamic properties and exergy values are presented in Table 5. The highest temperature value is 333°C, present on flow #4, which is high-pressure steam (2,039 kPa), coming from the boiler set. For the industrial process, in the way it was modelled, to work in compliance with the laws of thermodynamics, about 79 MW of energy power is needed in the sugarcane bagasse. Looking deeply at the exergy rates related to the mechanical power of the drive turbines (flows #53, #54 and #55), low exergy values can be seen that indicate the need for improvement in the equipment to increase its exergetic availability.

Table 6 Results of efficiencies and irreversibility of equipment

Equipment	η	ε	*Irreversibility*	
	(%)	*(%)*	*(MW)*	*%*
Boiler 1	77.92	30.21	48.02	28.02
Boiler 2	77.06	29.77	43.18	25.20
Boiler 3	75.71	29.11	31.37	18.31
Turbine 1	70.87	50.77	1.57	0.92
Turbine 2	80.16	49.32	1.63	0.95
Turbine 3	64.62	48.59	3.87	2.26
Turbine 4	---	46.62	1.25	0.73
Turbine 5	85.45	37.18	0.70	0.41
Turbine 6	92.45	66.01	0.57	0.33
Turbine 7	92.4	66.71	0.54	0.31
Desuperheater	---	65.71	0.38	0.22
Condenser	---	5.66	15.84	9.24
Pump 1	---	19.33	0.02	0.01
Deaerator	---	1.28	22.24	12.98
Pump 2	---	46.07	0.02	0.10
Total			*171.35*	*100.00*

According to the results presented in Table 6, the greatest irreversibilities are associated with boilers. This indicates the need to study the equipment to identify how to reduce the energy losses of the system. Analysing the results of exergetic efficiency of the set of turbines, it is noted that the lowest value is 37% in turbine 5. This result is different from the efficiencies of turbines 6 and 7 which are part of the same set of turbines that drive the plant's mechanical equipment. The discrepancy was since the equipment was operating in a low condition of mechanical maintenance at the end of the season.

Cost rates and SPECOs are presented in Table 7. Flow #18 indicates that for each GJ of energy available in the sugarcane bagasse, there is a monetary cost of approximately R$8.83. The production of steam to meet the demands of the turbines costs R$63.88 for each GJ of energy (flow #1). There is an energy and monetary waste associated with the steam lost by the boiler, represented by flow # 20. It is R$1,219 for each hour of equipment operation, indicating a strong need for improvement in the equipment.

Table 7 Exergetic costs

#	*Ex (MW)*	*c (R$/GJ)*	$\dot{C}$ *(R$/h)*	#	*Ex (MW)*	*c (R$/GJ)*	$\dot{C}$ *(R$/h)*
1	42.85	63.88	9,854.00	13	0.88	687.70	2,169.00
2	35.11	0.00	0.02	14	1.35	974.40	4,750.00
3	7.75	0.02	0.49	15	0.05	974.40	167.40
4	18.01	0.00	0.01	16	0.00	58,913.00	28.99
5	3.83	0.02	0.24	17	1.50	882.00	4,750.00
6	0.78	974.40	2,719.00	18	198.94	8.83	6,322.00
7	17.160	35.03	2,164.00	19	1.20	0.00	0.00
8	0.00	58,908.00	5.71	20	38.58	8.77	1,219.00
9	16.78	35.92	2,170.00	21	8.49	0.01	0.37
10	0.87	692.10	2,169.00	22	2.30	0.04	0.37
11	0.01	6382.00	187.70	23	0.03	3.43	0.37
12	0.08	692.10	188.40	24	0.31	0.33	0.37

Table 8 Exergoeconomic results by equipment

Equipment	*ε (%)*	E_D *(MW)*	c_F *(R$/GJ)*	c_P *(R$/GJ)*	$\dot{C}_D$ *(R$/h)*	$\dot{Z}_K$ *(R$/year)*	r_k *(%)*	f_k *(%)*
Boiler	25.60	120.20	8.77	34.28	3,808.00	5,632.00	290.70	0.04
Power generation turbines	49.64	8.61	0.00	0.01	0.02	1,408.00	9,408.00	98.92
Mechanic generation turbines	58.84	1.61	0.02	0.04	0.11	469.40	152.20	54.06
Desuperheater	65.42	0.38	35.03	53.58	41.95	5.63	52.94	0.00
Condenser	5.64	15.84	39.01	692.10	2,225.00	140.80	1,674.00	0.00
Deaerator	1.27	22.24	31.48	1,890.00	2,002.00	28.16	5,904.00	0.00
Pump #1	19.33	0.02	3.43	17.84	0.31	9.39	420.60	0.80
Pump #2	46.07	0.17	0.33	0.74	0.20	28.16	121.30	3.50

Other important results of the exergoeconomic evaluation are presented in Table 8. Following are the results of exergy efficiency, exergy destruction rate, specific costs of products and inputs, exergy destruction cost rate, annual cost rate per equipment, ratio specific costs of products and inputs and exergoeconomic factor. The lowest exergetic efficiencies of the installation are found in the deaerator and condenser, with 1.27% and 5.64%, respectively. The set of boilers has the highest value of exergy destroyed with

120 MW. Therefore, these three equipments deserve special attention regarding the design of improvements to reduce energy losses and reduce exergy destruction and increase exergetic efficiency.

To increase the energy efficiency of the boilers:

1. Remove as much moisture as possible from the sugarcane bagasse to reduce the effects of irreversibility arising from the chemical reactions of its combustion.
2. To increase the temperature of the air and water entering the boilers, with the help of air preheaters and economisers, devices available on the market.

The SPECO of the products is greater than the SPECO of the fuels for each of the equipment, which validates the model presented. Li et al. (2017) recommend that the parameters r_k and f_k should be analysed and discussed together to create the priority ranking in the need for energy optimisation. Thus, the highest r_k results together with the lowest f_k values should drive prioritisation. Following this concept, the order of prioritisation in energy optimisation for this work should be:

1. deaerator
2. condenser
3. generation turbines
4. boilers.

6 Conclusions

With this paper, it was possible to present a detailed step-by-step of a thermoeconomic evaluation of a sugar, alcohol and electricity production plant, from the burning of sugarcane bagasse. A study was carried out on the combustion of bagasse with 30% excess air in the process.

The results indicate that the greatest inefficiencies are present in boiler 1 (48 MW, 28%), boiler 2 (43 MW, 25%) and boiler 3 (31 MW, 18%), due to their irreversibilities characterised by the moisture present in the bagasse. sugarcane, due to the need to preheat the water entering the boiler and for better thermal insulation of the equipment. Consequently, the cost of exergy destruction from the sum of the three boilers is approximately R$3,808 per hour of operation at the plant. This means about 84% of all exergy destruction in the plant.

With the joint evaluation of the exergoeconomic factor and the relative cost difference between product and input, it was possible to present the ranking of prioritisation of the need for investment in energy optimisation of equipment:

1. deaerator
2. condenser
3. generation turbines
4. boilers.

Starting this process through the condenser and deaerator is more interesting due to the smaller financial resources needed and the low complexity of the equipment functionality. Although the generation turbines came in third place in this ranking, it is recommended that the optimisation should be carried out first in the boilers, as they are less complex equipment and have a lower maintenance cost.

The exergoeconomic modelling should be part of the energy assessment strategies for combined systems since it directs towards the most efficient solutions based on a complete and robust diagnosis. The evaluations developed and the results presented in this paper may encourage its application in different energy systems from the industrial sector to the third sector, such as: hospitals, hotels, shopping centres and others.

This work is important for the academic community, as it provides a detailed roadmap for thermoeconomic evaluations in industrial plants. This paper is part of the development of other works that will come soon:

1. parametric study for other plant conditions
2. a complete and detailed roadmap for the exergoenvironmental assessment of this plant
3. life cycle analysis of all equipment of the plant
4. optimisation proposal to increase energy efficiency and reduce environmental impacts.

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Nomenclature

$\dot{E}x$	Exergy	(MW)
$\dot{m}$	Mass flow rate	(kg/s)
n	Number of moles	
ex	Specific exergy	(kJ/kg)
$\dot{C}$	Exergy cost rate	(R$/h)
c	Specific exergy cost rate	(R$/GJ)
$\dot{Z}$	Total cost rate	(R$/year)
Z	Purchase cost	(R$)
r	Relative cost	(%)
f	Economic factor	(%)
i	Annual income rate	(%)
I	Irreversibility	MW
Subscripts		
Q	Heat	
w	Mechanical power	
i	Inlet	
o	Outlet	
0	State of reference	
EG	Exhaust gases	
Ch	Chemical	
Iso	Isentropic	
k	Component-related	
P	Product	
F	Fuel	
Greek letters		
ε	Exergy efficiency	(%)
η	Energy efficiency	(%)
φ	Maintenance factor	
β	Chemical exergy	
Abbreviations		
CRF	Recovery capital factor	
EES	Engineering equation solver	
PCI	Net calorific value	