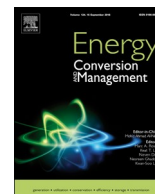




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Energy, exergy and exergoenvironmental analyses of a sugarcane bagasse power cogeneration system



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ABSTRACT

One of the strategies to reduce the environmental impacts associated with electricity is to employ renewable resources such as biomass or even waste. However, the evaluation of the sustainability of a power plant depends on the development of several analyses, which should encompass thermodynamic and environmental parameters. Energy, exergy, and exergoenvironmental assessments are carried out for a sugarcane bagasse cogeneration system, along with a Life Cycle Assessment for the Brazilian sugarcane bagasse, employing the Eco-indicator 99 method. The specific environmental impacts of electricity and steam are 6.023 mPt/MJ and 4.038 mPt/MJ, respectively, and the boiler feed pump and radiator presented the highest average environmental impact per exergy of fuel and product, respectively. The component with the highest exergoenvironmental factor was the furnace (60.32%), demonstrating margins for benefits in the formation of pollutants and destruction of exergy. Exergoenvironmental assessments can be utilized to support the adoption of more efficient (although more complex) cogeneration systems, especially in the aftermath of the COVID-19 crisis.

1. Introduction

Global energy demands increase in parallel with the technological and economic development of countries. Issues such as fossil fuel depletion, security of supply, and sustainability lead to the necessity of a more environmentally friendly energy matrix. According to the International Energy Agency [1], if consumption levels are maintained, the global demand for electricity will grow by 2.1% per year until 2040, with a 6% annual increase in bioelectricity generation until 2030 if a Sustainable Development Scenario (SDS) is considered [1]. Although there is an expected increase in the deployment of biomass, waste, and bagasse cogeneration power plants, the global energy matrix is predominantly based on non-renewable resources.

The Brazilian energy matrix is mostly composed of non-renewable sources (54.7%), with petroleum, diesel, and oil products accounting for 34.4% and natural gas with 12.5% [2]. When considering the offer of renewable energy, sugarcane biomass is responsible for 17.4%, hydraulic generation for 12.6% (including imports), firewood and charcoal contribute with 8.4%, and other renewables account for 6.9% [2].

The Brazilian electricity matrix in 2019 was 66.67% hydro, 9.28% natural gas, 9.15% wind, 8.25% sugarcane bagasse, 2.79% nuclear, 1.62% coal, 1.55% oil, and 0.69% solar [3]. Ferreira et al. [4] reported on the potential of biomass for electricity generation and concluded

that there are considerable margins for biomass to increase its contribution to the Brazilian electricity matrix. There are important missed opportunities for the generation of energy from urban pruning waste, as reported by Araújo et al. [5]. Significant environmental advantages were obtained when bioelectricity was generated, with possibilities for implementation of clean development mechanisms [6]. Coconut husk residues proved to be a technically and socially viable solution to produce electricity and fresh water for a small municipality [7]. Even landfill gas can be employed to power an on-site cogeneration plant, realizing economic benefits while also avoiding carbon emissions [8].

The economic feasibility of electricity cogeneration from sugarcane bagasse was confirmed by Souza et al. [9], who verified that the production of sugar and ethanol rejects, on average, 250 kg of bagasse and 200 kg of straw per milled tone of sugarcane. Bioelectricity generation from sugarcane bagasse in a sugar and ethanol industry resulted in considerable advantages in terms of avoided carbon emissions [10]. Bioelectricity from sugarcane bagasse (from now on referred to as bagasse) cogeneration can be very important in Brazil, as the sugarcane harvest period coincides with the period of low rainfall (low levels of hydroelectric reservoirs). Utilization of bagasse for energy purposes can ensure the energy self-sufficiency of an industry, with the possibility to sell surplus self-generated electricity and realize economic benefits.

Bagasse-based cogeneration has been the focus of many energy,

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economic, and exergy analyses. Fuel oil was replaced by bagasse in a sugar mill, and a techno-economic study and life cycle assessment of the cogeneration system indicated significant advantages favoring the use of bagasse [11]. Gongora and Villafrance [12] analyzed the current scenario of bagasse cogeneration in Belize and verified the potential for further expansion. The life cycle, social life cycle, and cost of living assessments were developed for bagasse cogeneration by Contreras-Lisperguer et al. [13], who confirmed bagasse as an adequate alternative for energy generation, with economic, environmental, and social advantages. Pérez et al. [14] investigated reheat and regeneration alternatives for cogeneration systems of the Brazilian sugarcane and alcohol sector and obtained increases in bagasse surplus and exergy efficiency. The economic feasibility of bagasse cogeneration with the sale of surplus self-generated electricity was reported by Souza et al. [9], who obtained a competitive production cost in comparison with other small power plants. Burin et al. [15] evaluated the integration of concentrated solar energy (CSP) with a bagasse cogeneration plant, considering additional hours of operation during off-season due to hybridization, and obtained an increase in electricity exports to the grid. An optimization model to support bagasse cogeneration in the sugarcane industry of Brazil revealed that long-term electricity contracting could offset the high capital costs [16]. Singh [17] studied a Kalina cycle power plant and harnessed cogenerated waste heat, obtaining increased energy and exergy efficiencies and concluding that additional drying of the bagasse would further increase these efficiencies.

However, modern systems for power generation must go a step further from the analysis of thermodynamic performance only and include environmental assessments due to the emergence of a generalized environmental conscience worldwide. Exergy provides information about the quality of energy and is very appropriate for evaluating the thermodynamic efficiency of energy conversion processes, playing an important role in increasing the use of green energy and technologies [18,19]. As discussed by Szargut et al. [20] and Tsatsaronis et al. [21], exergy can be combined with other indicators. Ascendency also synthesizes information about energy and matter flows, and when calculated on the basis of exergy flows, can help identify possibilities for the integration of energy systems and improvement in efficiency [22]. Environmental impacts obtained from a Life Cycle Assessment (LCA) can also be used with exergy streams, which constitute the exergoenvironmental assessment methodology for energy systems [23].

Focusing on the exergoenvironmental assessment, exergy analysis is complemented by environmental information provided by LCA, which quantifies the potential environmental impacts of a product, service, or activity, throughout its life cycle. LCA is standardized by the International Organization for Standardization (ISO) [24,25] and can utilize different environmental impact assessment methods, depending on the objective of the analysis. One of the most employed methods is the Eco-indicator 99 (EI99) [26], which is a global environmental indicator that encompasses eleven impact categories in a single score. Recent exergoenvironmental assessments have focused on a natural gas combined cycle with the integration of carbon capture and storage (CCS) and concentrated solar energy storage systems [27], and a eucalyptus biomass power plant [28]. Comprehensive exergoeconomic and exergoenvironmental analyses were developed for a system that combined a gas and steam turbine system and a solar field [29]. The exergoenvironmental analysis carried out by Baçoğul [30] showed that 98% of the total environmental impact of a geothermal plant was due to exergy destruction in the equipment. Montazerinejad et al. [31] developed thermodynamic, exergoeconomic, and exergoenvironmental investigations for a novel solar-based trigeneration system. Cavalcanti et al. [32] developed exergoeconomic and exergoenvironmental comparisons for a diesel-generator engine fueled with different diesel-biodiesel blends and found that the addition of biodiesel reduced the specific environmental impact of electricity. The same reduction was observed by Hong et al. [33] for a supercritical coal-fired power plant

with a purification system. Due to the importance of sugarcane for the Brazilian economy, Silva et al. [34] reported on the sustainable enhancement of sugarcane production for energy purposes in hot climates.

Exergoeconomic assessments have been carried out for bagasse-fueled cogeneration systems. However, to the best of the authors' knowledge and based on systematic reviews, there are no studies focused on exergoeconomic analysis of these, and this research aims to fill this knowledge gap. The overarching aim of this work is to apply the exergoenvironmental methodology to a bagasse-fueled cogeneration system, which generates steam and electricity. The novelties of this research are listed, aimed at further expanding the existing knowledge base: i) application of the exergoenvironmental analysis approach, based on the Eco-indicator 99 method, to a cogeneration plant fueled with sugarcane bagasse; ii) use of real data on the performance of cogeneration plants in Brazil; iii) development of a Life Cycle Assessment for sugarcane bagasse, and iv) evaluation of the environmental impact rate per exergy of electricity and comparison with other conventional and renewable sources of electricity generation

Exergoenvironmental balances are developed to quantify the environmental impact of each component within the system, obtaining the environmental impact rate per exergy unit of electricity and steam. The exergoenvironmental factors of all system components are evaluated to determine the components with the lowest environmental performance and to provide information on trends and possibilities for improvement in the project. The results provide information about a bagasse-fired plant and enable a detailed comparison with literature data. These assessments aid in the decision-making process, guiding investments to the production of environmentally friendly electricity.

2. Materials and methods

This section presents the sugarcane bagasse cogeneration system and provides details on the energy, exergy, and exergoenvironmental assessments.

2.1. Description of the power plant

The sugarcane bagasse cogeneration system studied herein is located in Northeast Brazil. The system produces 10.94 MW of thermal energy (steam) and 33 MW of electricity, where all the steam and 11 MW of electricity are used in the plant (22 MW electricity is sold to the electric concessionaire). Fig. 1 depicts the schematic configuration of the cogeneration system.

Ambient air (#21) is heated in the radiator (RAD), follows to Air heater 1 (AH1) and Air heater 2 (AH2), and enters the furnace (#2). The sugarcane bagasse processed by the mills (#1) is mixed and burned with heated air in the furnace, producing exhaust gases (#3). These gases flow into the superheater (SH) producing superheated steam (#16), into the evaporator producing saturated steam (#14), into economizer 2 and 1 producing hot water (#13 and #12) and into air heaters 2 and 1 heating the air (#2 and #3). The superheated steam (#16) at 479.4 °C and 65.67 bar from superheater drives the back-pressure steam turbine (BPST) (#19) and the condensation extraction steam turbine (CEST) (#20), with output pressures of 1.29 and 0.14 bar, respectively. These turbines generate 8.0 MW and 24.7 MW of electrical power in generators 1 and 2 (#35, #36), respectively. The output steam from BPST is used as process thermal energy (#24), and the remaining steam enters the deaerator (DEA) (#31).

The output steam from CEST (#25) changes phase in the condenser (COND), becoming a saturated liquid (#26) and returns to the deaerator (DEA) (#26). The process steam returns to the deaerator (#29), and the losses of steam are supplied as liquid water (#30). A portion of saturated steam from the evaporator (#17) is condensed in the radiator before returning to the deaerator (#18). The water inlets to the deaerator are mixed and heated to remove the dissolved oxygen

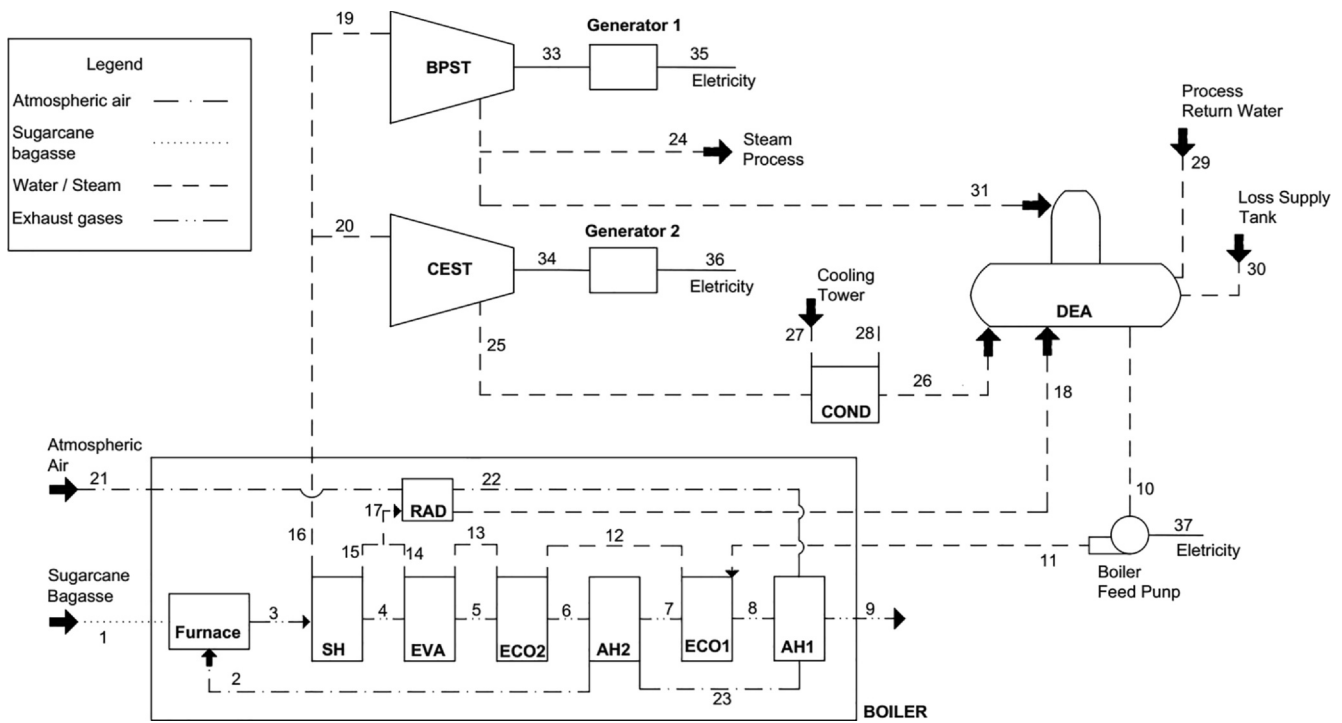


Fig. 1. Schematic diagram of the cogeneration system.

Table 1
Technical specifications of the boiler.

| Parameter | Unit | Value |
|---------------------------|-------|-------------------|
| Nominal Steam Production | ton/h | 200 |
| Nominal pressure steam | bar | 67 |
| Hydrostatic test pressure | bar | 74 |
| Steam temperature | °C | 520 |
| Steam condition | - | Superheated steam |
| Boiler fuel | - | Sugarcane bagasse |
| Fuel humidity | % | 50 |
| Fuel consumption | kg/h | 86,956 |
| Excess air | % | 30 |
| Water circulation | - | Natural |
| Water treatment | - | Demineralization |

from the water. The output steam of the deaerator (#10) is compressed in a pump before entering the economizer 1 (#11) and returning to the power plant cycle. Table 1 shows the technical data of the boiler, according to the manufacturer.

Real operation data was collected *in situ*, and steady state conditions are considered for the system:

- Water enters economizer 1 at 118.7 °C and 9050 kPa, enters economizer 2 at 163.8 °C and 8688 kPa, enters the evaporator at 231.8 °C and 8340 kPa; enters the superheater as saturated steam at 283.8 °C and 6785 kPa, and exits the boiler in the superheated state with 479.4 °C and 6785 kPa. Replacement water accounts for process losses and is assumed to be 5% of the mass flow entering the boiler.
- The temperature and water pressure in the deaerator are 117 °C and 180.3 kPa, respectively.
- Atmospheric air is 25 °C and 101.15 kPa. The air exchanges heat in the radiator and leaves at 67 °C, flowing through the air heaters and entering the furnace at 308.2 °C, with constant pressure.
- The humidity of sugarcane bagasse is 50% (mass basis).
- The temperature variation of the water in the cooling tower is 15 °C.
- The isentropic efficiency of the boiler feed pump is 70%.
- The electrical powers of generators 1 and 2 are 8094 kW and

24761 kW, respectively, with 96% efficiency.

2.2. Energy analysis

Combustion is a chemical reaction that results in energy and combustion products. The main chemical elements present in the usual fuels are carbon, hydrogen, and sulfur, the latter contributing insignificantly to the production of energy but considerably to environmental pollution [35]. The sugarcane bagasse presents interesting chemical properties such as low chlorine, phosphorus, and ash contents. Table 2 shows the elemental analysis of the dry sugarcane bagasse and ash employed herein [36].

The composition of wet bagasse (mass basis) is 24.32% C, 2.935% H₂, 0.02% S, 0.08% N₂, 21.425% O₂, 50% water (H₂O_(l)) and 1.22% ash. According to Bejan et al. [37], the volumetric composition of moist atmospheric air used for combustion can be considered as 20.59% O₂, 77.48% N₂, 1.9% H₂O_(g) and 0.03% CO₂. The molar fractions of wet bagasse components (carbon, hydrogen, oxygen, nitrogen, sulfur, water, and ash) must be calculated. The combustion reaction can be written per kmol of wet bagasse, as Equation (1):

Table 2
Mass composition of sugarcane bagasse (dry) and ash.

| Bagasse Composition (dry base) | Mass Composition (%) | Ash Composition (dry) | Mass Composition (%) |
|--------------------------------|----------------------|--------------------------------|----------------------|
| Carbon | 44.80 | SiO ₂ | 73.00 |
| Hydrogen | 5.40 | Al ₂ O ₃ | 5.00 |
| Oxygen | 39.60 | Fe ₂ O ₃ | 2.50 |
| Nitrogen | 0.40 | MgO | 2.10 |
| Sulfur | 0.01 | CaO | 6.20 |
| Ash | 9.79 | Na ₂ O | 0.30 |
| Total | 100 | K ₂ O | 3.90 |
| | | P ₂ O ₅ | 1.00 |
| | | Others | 6.00 |

$$\begin{aligned}
& [0.2794 \cdot C + 0.2007 \cdot H_2 + 0.09271 \cdot O_2 + 0.00107 \cdot N_2 + 0.00002337 \\
& \cdot S + 0.4159 \cdot H_2O_{(l)} + 0.01021 \cdot Ash] + \varphi_{air} \\
& \cdot x [O_2 + 3.763N_2 + 0.092H_2O_{(g)} + 0.0015CO_2] \rightarrow \beta_1 \cdot CO_2 + \beta_2 \cdot H_2 \\
& \quad O + \beta_3 \cdot O_2 + \beta_4 \cdot N_2 + \beta_5 \cdot SO_2 + Ash \quad (1)
\end{aligned}$$

φ_{air} is the theoretical amount of air, and $\varphi_{air} > 1$ indicates excess air. x is the minimum consumption of oxygen moles per fuel mole for complete combustion in a stoichiometric reaction with no excess air. β represents the stoichiometric coefficients of gaseous combustion products evaluated by chemical species balance. φ_{air} is considered to be 1.3 and $x = 0.2871$ kmol O_2 /kmol fuel.

The energy balance in the boiler furnace was carried out according to Moran et al. [35] using the first law of thermodynamics for reagent systems, as shown by Equation (2):

$$\dot{Q}_{CV} + \sum_R n_{in} (h_f^- + \Delta h^-)_{in} = \sum_P n_{out} (h_f^- + \Delta h^-)_{out} + \dot{W}_{CV} \quad (2)$$

n is the number of moles of reactant and products in the combustion reaction, h_f^- is the enthalpy of formation of each substance, and Δh^- is the variation of the formation enthalpy in relation to the dead state. Subscripts R and P correspond to the reagent and the product, respectively. The formation enthalpy of sugarcane bagasse was evaluated for the complete combustion reaction using pure oxygen, based on Sonntag et al. [38].

The High Heating Value (HHV) is calculated through the correlation studied by Channiwala and Parikh [39], which estimates the HHV of solid, liquid, and gaseous fuels as expressed by Equation (3):

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211A \quad (3)$$

C, H, O, N, S and A represent the content of carbon, hydrogen, oxygen, nitrogen, sulfur and ash of the material, respectively, expressed as percentages of mass on a dry basis: $0\% \leq C \leq 92.25\%$, $0.43\% \leq H \leq 25.15\%$, $0.00\% \leq O \leq 50.00\%$, $0.00\% \leq N \leq 5.60\%$, $0.00\% \leq S \leq 94.08\%$, $0.00\% \leq A \leq 71.4\%$, and $4.745 \text{ MJ/kg} \leq HHV \leq 55.345 \text{ MJ/kg}$.

The relationship between the Low Heating Value (LHV) and HHV depends on the water formed due to the amount of hydrogen present in the fuel and the moisture present in the fuel, according to Virmond et al. [40]:

$$LHV = HHV - h_{LV} \cdot (9H + W) \quad (4)$$

h_{LV} is the enthalpy of water vaporization at atmospheric pressure, in (kJ/kg). H and W are the mass fractions of hydrogen and moisture, respectively.

The mass and energy balances considering steady-state are applied to the energy system to find the mass flow rates, thermodynamic properties of each flow, the power of the system, and the thermal energy of the process [35,38]. The effects of kinetic and potential energy are not considered.

2.3. Exergy analysis

The exergy of a thermodynamic system is the maximum theoretical useful work (shaft work or electrical work) that can be produced by a system or flow of mass or energy in equilibrium with a reference environment [18,41]. The reference environment (dead state), is 25 °C and 101.15 kPa. Exergy uses the principle of energy conservation (incorporated in the first law of thermodynamics) together with the principle of non-conservation of entropy (incorporated in the second law) and can be applied to the analysis, design, and improvement of energy systems. The exergy of material streams is composed of chemical and physical exergy portions. Kinetic and potential exergies can be disregarded [23]. For water flows throughout the system (different states), physical exergy is obtained, with non-significant chemical

exergy. The chemical exergy of sugarcane bagasse is estimated using the method reported by Szargut and Styrylka within Qian et al. [42], in which the chemical exergy of organic fuels for $\left(\frac{O}{C} \leq 2\right)$, with the exception of wood, is described by Equations (5) and (6):

$$e^{CH} = \beta \cdot (LHV + W \cdot h_{LV}) + 9682 \cdot S + e_{ash} \cdot A + e_w \cdot W \quad (5)$$

$$\beta = \frac{\left(1.044 + 0.0160 \frac{H}{C} - 0.3493 \frac{O}{C} \left(1 + 0.0531 \frac{H}{C}\right) + 0.0493 \frac{N}{C}\right)}{\left(1 - 0.4124 \frac{O}{C}\right)} \quad (6)$$

β is the ratio of chemical exergy to the net (low) heat value. e_{ash} and e_w are the specific chemical energies of ash and water, respectively, which are considered negligible herein.

The chemical exergy of a gaseous mixture can be calculated as Equation (7) [37]:

$$e_g^{CH} = \sum_i y_i \cdot e_{CH}^0 + R \cdot T_0 \cdot \left(\sum_i y_i \cdot \ln(y_i) \right) \quad (7)$$

y_i is the molar fraction of the mixture component, R is the universal gas constant (8.3145 kJ/(kmol.K)), and e_{CH}^0 is the standard chemical exergy of each substance according to Kotas [43].

For the exergy assessment, there are basically two approaches to define the exergy and exergy cost balances [44]: the first approach groups exergy flows into inlets and outlets regardless of the economic purpose of the flows (physical approach, which relies on the physical structure of the system), and the second is based on a functional approach (based on the functional diagram, which redraws the physical structure of the system as a network of exergy interactions).

The exergy analysis is based on the Specific Exergy Costing (SPECOC) approach, developed by Lazzaretto and Tsatsaronis [45]. Each component k of the system is characterized by the definition of its product ($\dot{E}_{P,K}$) and fuel ($\dot{E}_{F,K}$) exergies. According to the definitions of each component and their function within the energy system, the product (P) principle refers to the exergy supply to an exergy stream within the component being considered. The fuel (F) principle refers to the depletion of exergy from an exergy stream within the component. When the energy system includes a chemical reaction with change of chemical content, the specific chemical and physical exergies must be separated. Table 3 shows the fuel and product exergy for each system component.

The exergy efficiency (ε_K) of the k th component is defined as the ratio between the exergies of the product and fuel [37], and shown in Equation (8):

$$\varepsilon_K = \frac{\dot{E}_{P,K}}{\dot{E}_{F,K}} \quad (8)$$

The destruction of exergy $\dot{E}_{D,K}$ is a direct measure of thermodynamic inefficiencies within the k th component and is calculated by Equation (9):

$$\dot{E}_{D,K} = \dot{E}_{F,K} - \dot{E}_{P,K} \quad (9)$$

The exergy destruction rate $y_{D,K}^*$ compares the destruction of exergy within the k th component with the destruction of exergy within the overall system ($\dot{E}_{D,tot}$), and is given by Equation (10):

$$y_{D,K}^* = \frac{\dot{E}_{D,K}}{\dot{E}_{D,tot}} \quad (10)$$

2.4. Exergoenvironmental analysis

The attribution of the results of the environmental analysis to the flows of exergy is carried out in a similar way to the allocation of costs to the flows of exergy in the exergoeconomic analysis [37] and follows the SPECOC method [45].

The exergoenvironmental assessment [23] quantifies the environmental performance of an energy system. EI99 was employed to express

Table 3
Structure of products and fuels exergy of all system components.

| Component | Fuel | Product |
|------------------|---|--|
| Furnace | \dot{E}_1 | $\dot{E}_3 - \dot{E}_2$ |
| Super Heater | $\dot{E}_3 - \dot{E}_4$ | $\dot{E}_{16} - \dot{E}_{15}$ |
| Evaporator | $\dot{E}_4 - \dot{E}_5$ | $\dot{E}_{14} - \dot{E}_{13}$ |
| Radiator | $\dot{E}_{17} - \dot{E}_{18}$ | $\dot{E}_{22} - \dot{E}_{21}$ |
| Economizer #2 | $\dot{E}_5 - \dot{E}_6$ | $\dot{E}_{13} - \dot{E}_{12}$ |
| Air Heater #2 | $\dot{E}_6 - \dot{E}_7$ | $\dot{E}_2 - \dot{E}_{23}$ |
| Economizer #1 | $\dot{E}_7 - \dot{E}_8$ | $\dot{E}_{12} - \dot{E}_{11}$ |
| Air Heater #1 | $\dot{E}_{23} - \dot{E}_{22}$ | $\dot{E}_8 - \dot{E}_9$ |
| Condenser | $\dot{E}_{25} - \dot{E}_{26}$ | $\dot{E}_{28} - \dot{E}_{27}$ |
| Deaerator | $\dot{m}_{31} \cdot (e_{31}^{PH} - e_{10}^{PH}) + \dot{m}_{32} \cdot (e_{32}^{PH} - e_{10}^{PH})$ | $\dot{m}_{26} \cdot (e_{10}^{PH} - e_{26}^{PH}) + \dot{m}_{29} \cdot (e_{10}^{PH} - e_{29}^{PH}) + \dot{m}_{30} \cdot (e_{10}^{PH} - e_{30}^{PH})$ |
| Boiler Feed Pump | \dot{E}_{37} | $\dot{E}_{11} - \dot{E}_{10}$ |
| BPST | $\dot{E}_{19} - (\dot{E}_{31} + \dot{E}_{24})$ | \dot{E}_{33} |
| CEST | $\dot{E}_{20} - \dot{E}_{25}$ | \dot{E}_{34} |
| Generator #1 | \dot{E}_{33} | \dot{E}_{35} |
| Generator #2 | \dot{E}_{34} | \dot{E}_{36} |
| Total Plant | \dot{E}_1 | $\dot{E}_{35} + \dot{E}_{36} + \dot{E}_{24} - \dot{E}_{37}$ |

the environmental impacts obtained via LCA and indicates the environmental impact in terms of a single index measured in points (Pts) or milipoints (mPts). One point represents one-thousandth of the annual environmental load of one average European inhabitant [26].

The environmental impact rate \dot{B}_k is the environmental impact of the ecological indicator per unit of time (Pt/s or mPt/s). The specific exergy-based environmental impact b_k (also called specific environmental cost) is the average environmental impact rate per exergy unit (Pt/exergy or mPt/exergy). The environmental impact rate is the product of its exergy rate \dot{E}_k by the specific environmental impact b_k , represented by Equation (11) [23]:

$$\dot{B}_k = b_k \cdot \dot{E}_k \quad (11)$$

The environmental impact balances of the kth component are expressed by Equations (12) and (13):

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k + \dot{B}_k^{PF} \quad (12)$$

$$b_{P,k} \cdot \dot{E}_{P,k} = b_{F,k} \cdot \dot{E}_{F,k} + \dot{Y}_k + \dot{B}_k^{PF} \quad (13)$$

$\dot{B}_{P,k}$ and $\dot{B}_{F,k}$ represent the environmental impact rates of the product and fuel [mPt/s], respectively, $b_{P,k}$ and $b_{F,k}$ are the corresponding average environmental impacts per unit of exergy [mPt / kJ] for product and fuel, respectively, \dot{Y}_k is the environmental impact rate of the component [mPt/s], and \dot{B}_k^{PF} represents the environmental impact rate of the formation of pollutants [mPt/s].

The component-related environmental impact (\dot{Y}_k) encompasses the impacts of construction, operation/maintenance, and disposal of equipment. For the analysis of the equipment throughout its life cycle, it is necessary to estimate the weight and the environmental impact per mass unit via LCA. Cavalcanti [29] presented several relationships for the calculations of \dot{Y}_k . The environmental impact rate of a component is the ratio between its environmental impact (mPt) and the operation time. Herein the operation time of the plant is 7000 h per year with a lifetime of 25 years.

The term \dot{B}_k^{PF} represents the rate of environmental impact related to pollutant formation in the component. The combustion of sugarcane bagasse produces pollutants that must be considered in the environmental impact of the power plant. The formation of pollutants is defined only when a chemical reaction occurs at the site - in all other cases the term is equal to zero. The formation of pollutants is calculated by Equation (14):

$$\dot{B}_k^{PF} = \sum_i b_i^{PF} \cdot (\dot{m}_{out} - \dot{m}_{in})_i \quad (14)$$

\dot{m}_{out} and \dot{m}_{in} are the output and input mass flows of pollutants into a

component, respectively, and b_i^{PF} is the specific environmental impact of each pollutant emitted. These values for CO₂ and SO₂ are 5.45 and 1499.37 mPt/kg [26].

Exergoenvironmental variables are used to assess the environmental performance of the system components. These variables are defined for all components of the system in analogy with the definition of exergoeconomic variables in exergoeconomics [23].

The rate of environmental impact $\dot{B}_{D,k}$ associated with the destruction of exergy $\dot{E}_{D,k}$ within the kth component can be calculated by Equation 15:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}_{D,k}; \quad (15)$$

The total environmental impact associated with the kth component is provided by $\dot{B}_{TOT,k}$ and identifies the environmental relevance of the component in the system being studied as expressed by Equation 16:

$$\dot{B}_{TOT,k} = \dot{B}_{D,k} + \dot{Y}_k + \dot{B}_k^{PF}$$

The relative difference of environmental impact ($r_{b,k}$) and exergoenvironmental factor ($f_{b,k}$) are used to assess the exergoenvironmental performance of each component within the system. $r_{b,k}$ is the ratio of increase of the average environmental impact to the average environmental impact of the fuel and is given by Equation (17):

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}} \quad (17)$$

$r_{b,k}$ indicates the potential for reducing the environmental impact of a component [23]. A relatively high value of ($r_{b,k}$) indicates the components that can have their environmental impact of product reduced with less effort, in comparison with components with a lower $r_{b,k}$ value.

The exergoenvironmental factor expresses the relative contribution of the environmental impact related to the \dot{Y}_k component to the sum of the environmental impacts associated with the kth component:

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{B}_{D,k} + \dot{Y}_k + \dot{B}_k^{PF}} = \frac{\dot{Y}_k}{\dot{B}_{TOT,k}} \quad (18)$$

The component-related environmental impact \dot{Y}_k is dominant when the value of $f_{b,k}$ is higher than approximately 0.7; however, when exergy destruction is the dominant source of environmental impacts, the value of $f_{b,k}$ becomes lower than approximately 0.3 [23].

The cogeneration system presents dissipative components that destroy exergy without obtaining something thermodynamically useful, such as the condenser's expansion valve. These losses can be considered in the complete system by assigning a fictitious environmental impact rate associated with the dissipative component [45]. This assigned environmental impact is then distributed to the productive components,

using the entropy difference as a weighting factor. Dissipative losses were allocated to the superheater, evaporator, economizers, and air heaters.

The LCA of sugarcane bagasse was carried out with SimaPro software 9.0.0.49 [46], employing the Ecoinvent database [47] and environmental impact assessment method EI99 [26]. More details on the application of EI99 to energy systems can be consulted in Carvalho et al. [48]. Sugarcane bagasse production assumes sugarcane production on a plantation with a 5-year lifetime, and represents the average operation expenditures to produce sugarcane averaged throughout the entire lifetime (includes establishment, operation, and clearing of plantation) [47]. The dataset includes all machine operations and corresponding machine infrastructure and sheds. Direct field emissions are included. The transport of sugarcane to the refinery is included, along with its processing to bagasse, ethanol, and vinasse. System boundary is at the refinery. Treatment of waste effluents is not included as most wastewater is spread over the fields. Data is from various sugar and ethanol producers in Brazil (including literature data).

3. Results and discussion

Solution of Equation (2) yielded the formation enthalpy of wet sugarcane bagasse as -153.617 MJ/kmol, with a molar mass of 14.96 kg/kmol. From Equations (2) and (3), the LHV of wet bagasse is 7034 kJ/kg. Following the development of energy, exergy and exergoenvironmental balances, the mass flow rates (\dot{m}) were obtained, along with data on temperature (T), pressure (P), exergy rates (\dot{E}), environmental impact rates (\dot{B}), and specific environmental impacts (b), as shown in Table 4.

Table 4

Results of the energy, exergy and exergoenvironmental balances for the sugarcane bagasse cogeneration system.

| Point | Stream | \dot{m} [kg/s] | T [°C] | P [kPa] | \dot{E} [MW] | \dot{B} [mPt/s] | b [mPt/MJ] |
|-------|----------------|------------------|----------|---------|----------------|-------------------|------------|
| 1 | Bagasse | 24.15 | 25.00 | 101.2 | 230.958 | 162.6 | 0.704 |
| 2 | Air | 83.71 | 308.20 | 101.2 | 7.349 | 35.1 | 4.777 |
| 3 | Gas | 107.86 | 1,353.00 | 101.2 | 133.865 | 309.4 | 2.311 |
| 4 | Gas | 107.86 | 1,167.00 | 101.2 | 109.751 | 253.7 | 2.311 |
| 5 | Gas | 107.86 | 548.10 | 101.2 | 40.952 | 94.7 | 2.311 |
| 6 | Gas | 107.86 | 433.80 | 101.2 | 31.183 | 72.1 | 2.311 |
| 7 | Gas | 107.86 | 356.80 | 101.2 | 25.367 | 58.6 | 2.311 |
| 8 | Gas | 107.86 | 280.30 | 101.2 | 20.312 | 47.0 | 2.311 |
| 9 | Gas | 107.86 | 199.60 | 101.2 | 15.921 | 37.0 | 2.311 |
| 10 | Liquid | 53.02 | 117.00 | 180.3 | 2.639 | 15.4 | 5.823 |
| 11 | Liquid | 53.02 | 118.70 | 9050.0 | 3.186 | 19.7 | 6.166 |
| 12 | Liquid | 53.02 | 163.80 | 8688.0 | 6.027 | 33.5 | 5.560 |
| 13 | Liquid | 53.02 | 231.80 | 8340.0 | 11.888 | 58.8 | 4.942 |
| 14 | Steam | 53.02 | 283.80 | 6785.0 | 55.211 | 228.5 | 4.139 |
| 15 | Steam | 50.65 | 283.80 | 6785.0 | 52.741 | 218.3 | 4.139 |
| 16 | Steam | 50.65 | 479.40 | 6566.0 | 68.515 | 276.7 | 4.038 |
| 17 | Steam | 2.37 | 283.80 | 6785.0 | 2.469 | 10.2 | 4.139 |
| 18 | Liquid | 2.37 | 283.80 | 6785.0 | 0.796 | 3.3 | 4.139 |
| 19 | Steam | 22.51 | 479.40 | 6566.0 | 30.451 | 123.0 | 4.038 |
| 20 | Steam | 28.14 | 479.40 | 6566.0 | 38.064 | 153.7 | 4.038 |
| 21 | Air | 83.71 | 25.00 | 101.2 | 0 | 0 | 0 |
| 22 | Air | 83.71 | 67.00 | 101.2 | 0.232 | 6.9 | 29.840 |
| 23 | Air | 83.71 | 188.90 | 101.2 | 2.871 | 19.7 | 6.853 |
| 24 | Steam | 17.48 | 259.20 | 129.0 | 10.945 | 44.2 | 4.038 |
| 25 | Steam | 28.14 | 52.53 | 14.0 | 5.441 | 22.0 | 4.038 |
| 26 | Liquid | 28.14 | 52.53 | 14.0 | 0.139 | 0.6 | 4.038 |
| 27 | Liquid | 749.80 | 25.00 | 101.2 | 0 | 0 | 0 |
| 28 | Liquid | 749.80 | 45.00 | 101.2 | 2.014 | 0 | 0 |
| 29 | Liquid | 14.95 | 25.00 | 101.2 | 0 | 0 | 0 |
| 30 | Liquid | 2.53 | 25.00 | 101.2 | 0 | 0 | 0 |
| 31 | Steam | 5.03 | 259.20 | 129.0 | 3.147 | 12.7 | 4.038 |
| 32 | Liquid | 2.37 | 106.90 | 129.0 | 0.508 | 2.1 | 4.139 |
| 33 | Shaft Power | – | – | – | 8.431 | 66.1 | 7.839 |
| 34 | Shaft Power | – | – | – | 25.793 | 131.8 | 5.109 |
| 35 | Electric Power | – | – | – | 8.094 | 66.1 | 8.167 |
| 36 | Electric Power | – | – | – | 24.761 | 131.8 | 5.323 |
| 37 | Electric Power | – | – | – | 0.711 | 4.3 | 6.023 |

The combustion of wet sugarcane bagasse considered excess air as 30%, with an air–fuel ratio of 3.47 kg air per kg of bagasse. The mass composition of exhausted gases is 18.62% CO₂, 17.72% H₂O, 59.49% N₂, 4.16% O₂, and 0.00226% SO₂.

The powers of the turbines are 8.43 MW for BPST and 25.79 MW for CEST, at points 33 and 34, respectively. The isentropic efficiencies are 42.95% and 77.76%, respectively. The low value of the BPST efficiency is due to its operation at partial load. Although the nominal power of BPST is 15 MW, it only produces 8.43 MW. The efficiencies of the generator and pump are 96% and 70%, respectively.

The environmental impacts associated with ambient air and water were considered negligible. The result of sugarcane bagasse LCA is 6.73 mPt/kg bagasse, of which 3.16 mPt/kg were in the damage category of human health, 3.26 mPt/kg in ecosystem quality, and 0.31 mPt/kg in resources.

Sugarcane bagasse fuel presents a high value of chemical exergy rate. The environmental impact per exergy unit for BPST was 7.839 mPt/MJ, and for CEST it was 5.109 mPt/MJ. The low exergy efficiencies lead to these low values of specific environmental impact associated with electricity: the efficiencies are 51.54% and 79.06% for BPST and CEST, respectively. Rosen et al. [18] stated that as exergy efficiency is increased, the environmental impacts decrease.

The system produces 32.14 MW of net electrical power (two generators minus the power consumed by the pump) and produces 10.94 MW of process steam at point 24 of the cogeneration cycle (Fig. 1). According to the SPECOC approach, the environmental loads of the condenser (dissipative component) were charged to the boiler components. Therefore, the electricity generated by the cogeneration system has a specific environmental impact of 6.023 mPt/MJ or 21.68

Table 5
Exergy parameters of the components of the cogeneration system.

| Components | \dot{E}_F [kW] | \dot{E}_P [kW] | \dot{E}_D [kW] | ε [%] |
|------------------|------------------|------------------|------------------|-------------------|
| Furnace | 230,958 | 126,515 | 104,443 | 54.78 |
| Super Heater | 24,114 | 15,774 | 8,339 | 65.42 |
| Evaporator | 68,799 | 43,323 | 25,477 | 62.97 |
| Radiator | 1,673 | 232 | 1,441 | 13.87 |
| Economizer #2 | 9,769 | 5,861 | 3,908 | 59.99 |
| Air Heater #2 | 5,816 | 4,479 | 1,337 | 77.01 |
| Economizer #1 | 5,054 | 2,841 | 2,214 | 56.20 |
| Air Heater #1 | 4,391 | 2,638 | 1,753 | 60.08 |
| Condenser | 5,303 | 2,014 | 3,289 | 37.98 |
| Deaerator | 3,286 | 2,132 | 1,154 | 64.89 |
| Boiler Feed Pump | 711 | 547 | 163 | 77.04 |
| BPST | 16,360 | 8,431 | 7,929 | 51.54 |
| CEST | 32,623 | 25,793 | 6,830 | 79.06 |
| Generator #1 | 8,431 | 8,094 | 337 | 96.00 |
| Generator #2 | 25,793 | 24,761 | 1,032 | 96.00 |
| Plant | 230,958 | 43,253 | 169,645 | 18.73 |

mPt/kWh at point 37, and the specific environmental impact of the steam generated is 4.038 mPt/MJ at point 24.

The exergy balances were carried out for each component of the system, using the fuel (\dot{E}_F) and product (\dot{E}_P) exergy definitions shown in Table 3. Table 5 shows the exergy destruction rate (\dot{E}_D), and exergy efficiency (ε) for each component.

The results of the exergy analysis revealed that the highest fuel and product exergy values are located at the furnace, followed by the evaporator. The furnace converts the chemical exergy of bagasse into the thermal energy of exhaustion products. The evaporator converts the thermal energy of exhaust gases into the thermal energy of steam. Both components, furnace, and evaporator, present the highest exergy destruction.

The electrical generators have the highest exergy efficiencies, while the radiator presents the lowest exergy efficiency. The total exergy destroyed within the system is 169.6 MW, to which the boiler furnace contributes the most, with 104.4 MW. The reason for this is inherent to the nature of boilers, which destroy the chemical exergy of fuel.

The total exergy efficiency of the system is 18.73%. A similar value was obtained by Cavalcanti et al. [28], who used moist eucalyptus biomass and obtained an exergy efficiency of 16.89%, due to the high moisture content of the fuel (heat is consumed to evaporate this moisture). Singh [17] also obtained a similar result, with an exergy efficiency of 21.07% for a cogeneration plant fueled with sugarcane bagasse. These low efficiency values indicate margins for improving the performance of these plants, such as employing exhaust gases to reduce the biomass moisture.

The condenser is a component that presents low efficiency. Due to its dissipative character, its significance is considered only in the context of the overall thermal system. Despite the considerable high energy losses in the condenser, the exergy destruction is the lowest, which indicates that from the perspective of power production, the energy loss is not worthwhile due to its poor exergy content or low work production capability [17].

The BPST presents 51.54% exergy efficiency, against 79.06% for CEST. These results are due to the isentropic efficiencies of the turbines. A more efficient steam turbine (BPST) will improve the electrical power and will also enhance the global exergy efficiency. Fig. 2 shows the share of the overall destroyed exergy per component.

The furnace is responsible for the majority (61.57%) of exergy destruction in the system. Other studies that employed sugarcane bagasse presented similar results, where the highest destructions of exergy were identified at the boiler furnace, such as Singh [17], with 68.22%, and Pérez et al. [14], with 94.4% for the conventional case. Cavalcanti et al. [28] analyzed the combustion of eucalyptus biomass and also obtained the highest exergy destruction in the boiler, with 83.28%.

Table 6 presents the average environmental impact per exergy of

fuel (b_f) and product (b_p), environmental impact rate of exergy destruction (\dot{B}_D), environmental impact rate of pollutant formation (\dot{B}^{PF}), component-related environmental impact (\dot{Y}), sum of the environmental impacts of the component (\dot{B}_{Tot}), and exergoenvironmental factor (f_b).

The feed pump has the highest average environmental impact per exergy of fuel, because its fuel is the product of system (electricity). The radiator has the highest average environmental impact per exergy of product, as it increases the air temperature between points 21 and 22 using the condensation of steam. This higher value is due to a low increase in the air exergy rate with high exergy destruction within this process.

The furnace, followed by the radiator, presents the highest environmental impact rate associated with exergy destruction. Both components present the highest exergy destruction rate and together represent 35.09% of the overall exergy destruction rate. The furnace is the only component with the formation of pollutants. The combustion generates 0.186 kg of CO₂ and 0.022 kg of SO₂ per mass unit of sugarcane bagasse burned. Although the amount of CO₂ is higher than SO₂, the environmental impact of SO₂ is 275 times higher than environmental impact of CO₂. The emission of SO₂ represents 97.01% of the environmental impact rate associated with pollutant formation.

The superheater presents the highest component environmental impact rate, 594.5 mPt/h or 0.165 mPt/s. However, it has been demonstrated that the environmental impact rate of a component (\dot{Y}) does not significantly affect the total environmental impact ($\dot{B}_{Tot,k}$). In the case of the superheater, \dot{Y} only represents 0.84% of the overall environmental impact (19.44 mPt/s). The boiler furnace is the component with the highest total environmental impact, 185.3 mPts/s, due to the high impacts associated with the formation of pollutants (about 63.5% of the total impact of the furnace).

The formation of pollutants is equivalent to 31.20% of the total environmental impact. SO₂ is the major contributor to the environmental impacts, corresponding to 30.26% of the total environmental impact of the system.

The exergoenvironmental factors of the components were lower than 0.9%, except for the furnace, due to pollutant formation. A low value of f_b indicates that the environmental impact rate of exergy destruction is predominant. The condenser, boiler feed pump, and radiator present the lowest values. The condenser, as aforementioned, is a dissipative component and does not have a thermodynamic product – the condenser destroys exergy for the operation of the system.

The radiator presents the lowest exergy efficiency, 13.87%. If steam from point 24 was used instead of steam from point 14, a lower specific exergy is used as a fuel, leading to a lower rate of exergy destruction. A better configuration of the radiator's heat exchangers would bring benefits, along with a more efficient pump. The improvement of these two components will increase the environmental performance of the global system. The relative difference of environmental impact (r_b) of each component is shown in Fig. 3.

r_b represents the difference between the specific environmental impact of the product (b_p) and the fuel (b_f) [37]. A high value of r_b indicates that the average environmental impact of a component can be reduced with smaller effort than for a component with a lower r_b value. Of the components of the cogeneration system, the radiator stands out with $r_b = 620.9\%$, followed by the furnace with $r_b = 208\%$.

The environmental impact rate per exergy unit obtained for the cogenerated electricity from sugarcane bagasse was 21.68 mPt/kWh, while for process steam it was 4.03 mPt/MJ. Table 7 shows a comparison of the values obtained herein with scientific literature values.

The environmental impact rate per exergy unit of electricity obtained herein (21.68 mPt/kWh) is 22% lower than the value obtained by Cavalcanti et al. [28], but 60% higher than Casas-Ledón et al. [49]. The environmental impacts associated with municipal solid waste, sugarcane bagasse, and eucalyptus are, respectively, 0.12 mPt/MJ, 0.704 mPt/MJ and 9.975 mPt/MJ. Lower environmental impacts associated

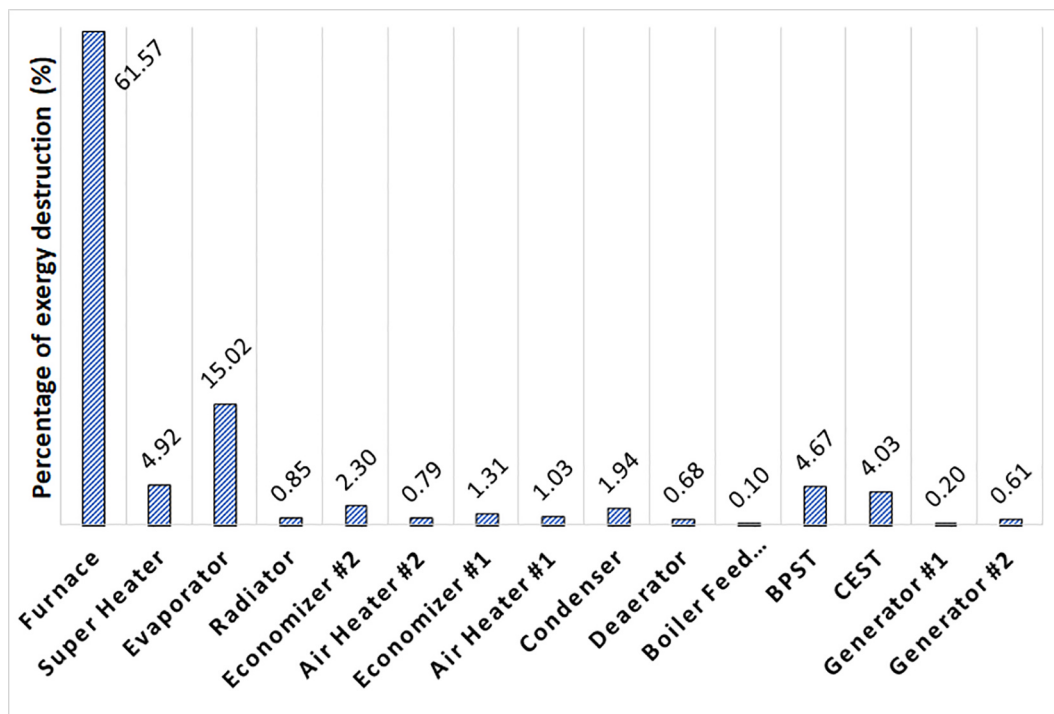


Fig. 2. Percentage of exergy destruction rate per component.

with the fuel will lead to lower environmental impacts associated with electricity. However, it must be pointed out that Casas-Ledón et al. [49] only takes into account the CO₂ emissions, while the other two other works considered SO₂ emissions.

Although Meyer et al. [23] presented a similar value for the environmental impact rate per exergy unit of electricity, the formation of pollutants was not considered in the combustion of woodchips. The environmental impact associated with woodchips is 1.353 mPt/MJ, much higher than the value for sugarcane bagasse. It was verified that the value obtained herein for the environmental impact rate per exergy unit of electricity is about half the value of the European Network of Transmission System Operators (contains 43 transmission system operators from 36 countries). When analyzing electricity mixes, the sources of generation and efficiency are critical: Greece and Italy have electricity mixes with the predominance of coal and natural gas power plants and hence the higher environmental impacts. On the other hand, France presents a higher contribution of nuclear power plants, leading to a lower value of environmental impacts.

As mentioned by Marques et al. [50], exergy-based assessments,

along with their discussions, can stimulate the adoption of co- and trigeneration systems, which are more efficient. At the time of writing, the coronavirus (COVID-19) crisis is having a significant impact across the energy sector and is hindering low-carbon energy transitions. Governments are drawing up stimulus plans to counter the economic damage from the coronavirus [51]. In the aftermath, governments will have to establish actions aimed at more affordable, secure, and sustainable energy systems in the longer term. That is where energy efficiency, implemented through cogeneration and trigeneration systems, can play an important role, improving economic competitiveness and providing more affordable energy while also reducing environmental impacts.

4. Conclusions

Energy, exergy, and exergoenvironmental analyses were carried out for a cogeneration plant fueled with sugarcane bagasse, which produced 22 MW of net electricity and 10.94 MW of heating. The formation enthalpy of wet sugarcane bagasse was calculated as -53.617 MJ/

Table 6
Exergoenvironmental variables.

| Components | b_f [mPt/MJ] | b_p [mPt/MJ] | \dot{B}_D [mPt/s] | \dot{B}^{PF} [mPt/s] | \dot{Y} [mPt/h] | \dot{B}_{Tot} [mPt/s] | f_b [%] |
|------------------|----------------|----------------|---------------------|------------------------|-------------------|-------------------------|-----------|
| Furnace | 0.704 | 2.168 | 73.51 | 117.7 | – | 185.30 | 60.320 |
| Super Heater | 2.311 | 3.700 | 19.28 | – | 594.50 | 19.44 | 0.849 |
| Evaporator | 2.311 | 3.918 | 58.89 | – | 48.98 | 58.90 | 0.023 |
| Radiator | 4.139 | 29.840 | 5.97 | – | 1.67 | 5.97 | 0.008 |
| Economizer #2 | 2.311 | 4.306 | 9.03 | – | 7.86 | 9.04 | 0.024 |
| Air Heater #2 | 2.311 | 3.446 | 3.09 | – | 18.26 | 3.09 | 0.164 |
| Economizer #1 | 2.311 | 4.881 | 5.12 | – | 4.92 | 5.12 | 0.027 |
| Air Heater #1 | 2.311 | 4.830 | 4.05 | – | 18.26 | 4.06 | 0.125 |
| Condenser | 4.038 | – | 13.28 | – | 0.70 | 13.28 | 0.001 |
| Deaerator | 3.853 | 5.939 | 4.45 | – | 6.42 | 4.45 | 0.040 |
| Boiler Feed Pump | 6.023 | 7.819 | 0.98 | – | 0.07 | 0.98 | 0.002 |
| BPST | 4.038 | 7.839 | 32.01 | – | 132.20 | 32.05 | 0.114 |
| CEST | 4.038 | 5.109 | 27.58 | – | 196.90 | 27.63 | 0.198 |
| Generator #1 | 7.839 | 8.167 | 2.64 | – | 32.78 | 2.65 | 0.343 |
| Generator #2 | 5.109 | 5.323 | 5.27 | – | 47.38 | 5.28 | 0.250 |

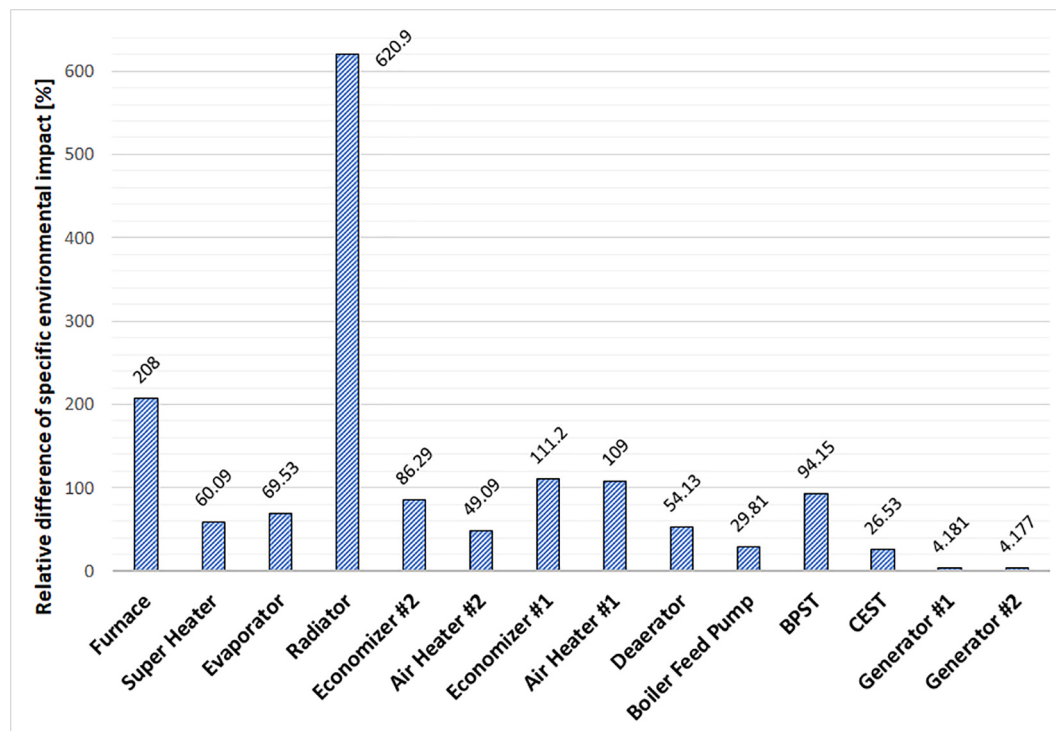


Fig. 3. Relative difference of environmental impact per component.

kmol. The environmental impact of sugarcane bagasse was determined from a Life Cycle Assessment as 6.73 mPt/kg.

The boiler's furnace presented an exergy destruction rate of 104.4 MW, representing 61.57% of the overall exergy destruction. The specific environmental impact of electricity and steam were, respectively, 21.68 mPt/kWh and 4.03 mPt/MJ.

The boiler feed pump and radiator presented the highest average environmental impact per exergy of fuel and product, respectively. The highest environmental impact rate associated with exergy destruction occurred in the radiator. The environmental impact rate of pollutant formation was 117.7 mPt/s, and SO₂ emission accounted for 97.01% of this value.

The environmental impact rates of the components of the system were not significant when analyzing the total environmental impact. From an exergoenvironmental point of view, decision making for improvements is based on the value of the exergoenvironmental factor. The component with the highest exergoenvironmental factor was the furnace (60.32%), highlighting the importance of improvements regarding the formation of pollutants and also the impact of the destruction of exergy. The remaining components of the system presented

exergoenvironmental factors under 1%, indicating that the predominant source of environmental impacts is due to the destruction of exergy.

A case is made on the utilization of exergy-based assessments, such as the exergoenvironmental assessment, to incentivize the adoption of more efficient, although more complex, cogeneration systems, especially in the aftermath of the COVID-19 crisis.

CRedit authorship contribution statement

Eduardo J.C. Cavalcanti: Supervision, Conceptualization, Methodology, Software, Validation, Writing - original draft, Visualization. **Monica Carvalho:** LCA and software; writing - reviewing; state of art; editing. **Daniel R.S. da Silva:** Investigation, Validation, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

Table 7

Comparison of environmental impact rate per exergy unit of electricity.

| Plant / system | Fuel | Emissions | Environmental impact rate of products | Reference |
|--|---------------------------|---|--|-------------------------|
| Cogeneration system with sugarcane bagasse | Sugarcane bagasse biomass | CO ₂ , SO ₂ | - Electricity (21.68 mPt/kWh)- Process steam (4.03 mPt/MJ) | This study |
| Eucalyptus-fueled thermoelectric power plant | Eucalyptus biomass | CO ₂ , CO, SO ₂ , NO, NO ₂ | - Electricity (27.77 mPt/kWh) | Cavalcanti et al. [28] |
| Municipal solid waste gasification system integrated with a combined cycle | Municipal solid waste | CO ₂ , CO, CH ₄ | - Electricity (13.5 mPt/kWh)- District Heating (0.77 mPt/MJ) | Casas-Ledón et al. [49] |
| Bioenergy conversion plant (fuel cell + biomass gasification process) | Wood chip biomass | Not considered | - Electricity (20.9 mPt/kWh) | Meyer et al. [23] |
| Electric mix (low voltage) | - | - | 105 mPt/kWh | Ecoinvent [47] |
| Greece | - | - | 39.4 mPt/kWh | |
| Italy | - | - | 13 mPt/kWh | |
| France | - | - | 39.9 mPt/kWh | |
| European Network of Transmission System Operators | - | - | | |

influence the work reported in this paper.

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