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THERMODYNAMIC STUDY THROUGH EES OF THE USE OF BIOGAS IN POWER SYSTEMS IN SUGAR AND ETHANOL PLANTS

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Abstract. *Biogas from vinasse represents an alternative source of renewable energy. About 10 to 15 liters of vinasse are generated for each liter of ethanol in the distillation stage and, on the global scenario, Brazil is among the largest producers of ethanol derived from sugarcane. Vinasse is commonly used in fertigation, and its decomposition emits methane, a greenhouse gas (GHG) 21 times more harmful than carbon dioxide. The objective of this study is to estimate the electrical and thermal energy production, as well as the energy efficiency, in sugar and ethanol mills in cogeneration systems using biogas. Carbon credits were also evaluated. The EES® software was used to perform the analyses, as well as for the mass and energy balance. Data from the literature was used to simulate and compare the energy efficiency of cogeneration with biogas. The preliminary results obtained for one of the analyzed plants showed that the energy efficiency and the installed power were 41.5% and 53% higher, respectively, when it consumed only biogas from vinasse, besides generating carbon credits. Therefore, the combined cycle associated with cogeneration is capable of meeting the energy demand of production in addition to making the plants presented more energy efficient.*

Keywords: *biogas, cogeneration, combined cycle, sustainable energy, sugar and alcohol plants*

1. INTRODUCTION

Power generation through renewable energy sources will be critical in a low-carbon future. The physical impacts of climate change are among the challenges to be addressed when implementing renewable energy deployment, as these impacts have implications for the reliability and performance of the overall energy system (Solaun and Cerdá, 2019). Currently, fossil fuels are the main sources for global energy sectors (Ho, 2016). On the other hand, their use entails a large amount of greenhouse gas (GHG) emissions, intensifying global warming. Despite the environmental problems caused by these fuels, they continue to be widely employed for energy generation and consumption (Ghirlanda, 2018).

In this scenario, the biofuel ethanol, which is produced from biomass, presents itself as an environmentally friendly alternative to the use of fossil fuels. The US accounts for about 60% of the world production of this biofuel; in second place is Brazil with 32%, followed by China, Canada, India, and Argentina (REN21, 2019). Between 2019 and 2020, around 35.5 billion liters of ethanol derived from sugarcane were produced worldwide, which represents a 7% increase over the amount produced in 2018. With regard to ethanol derived from corn, the increase was 114%, having been about 1.69 billion liters (Conab, 2019).

Despite the fact that ethanol production is well established on a large scale in countries like Brazil, the process of obtaining this biofuel generates large volumes of wastewater, especially vinasse (also called stillage), a substance that can pose a serious environmental problem depending on its destination (Moraes *et al.*, 2015). Vinasse is the liquid fraction generated from ethanol rectification and distillation operations; it is a sulfur-rich, low pH effluent that is dark in color and odoriferous, and is produced in volumes up to 20 times those of ethanol. Traditional wastewater treatments, such as bioprocessing, advanced oxidative processes, anaerobic digestion (AD), and chemical-based processes, have been applied to vinasse management (Reis and Hu, 2017).

Although most of the use of this byproduct is in fertigation practices, whose large-scale application is also associated

with environmental problems (Silva *et al.*, 2021), vinasse can represent a key factor in improving the profitability and environmental outcomes of a sugarcane/ethanol plant. The application of some improvement solutions to the use of vinasse can represent, among other things, additional sources of energy, since this material constitutes one of the resources with a high potential for biogas production. Biogas production from vinasse has both economic and environmental advantages (Reis and Hu, 2017; Parsaee *et al.*, 2019). According to Parsaee *et al.* (2019), 22.4 ggaliters of vinasse are currently produced worldwide, which has the potential to produce 407.68 ggaliters of biogas. This potential can be considered as a significant source of renewable energy.

Thus, this study aims to estimate the production of electric and thermal energy, as well as the energy efficiency, in sugar and ethanol mills in cogeneration systems using biogas, and to evaluate the carbon credits obtained from this implementation. With this, it is also possible to compare the energy efficiency of cogeneration with biogas with the efficiency of cogeneration with other fuels.

2. REVIEW

2.1 Vinasse

Among several energy solutions with origin in the use of biomass, the vinasse has gained much prominence due to the large sugar and alcohol production of the Brazilian industry. The vinasse is a residual liquid that originates from the distillation process of the alcoholic substance called "wine", which is obtained from the fermentation process to obtain alcohol (Silva *et al.*, 2021).

Brazil is currently the second largest ethanol producer in the world, producing from 2015 to 2016, 30 billion liters of ethanol, generating approximately 300 billion liters of vinasse, as it is estimated that for every liter of ethanol, approximately 10 liters of vinasse is generated (Calegari, 2017). Figure 1 illustrates in a very detailed way an example of the ethanol production chain.

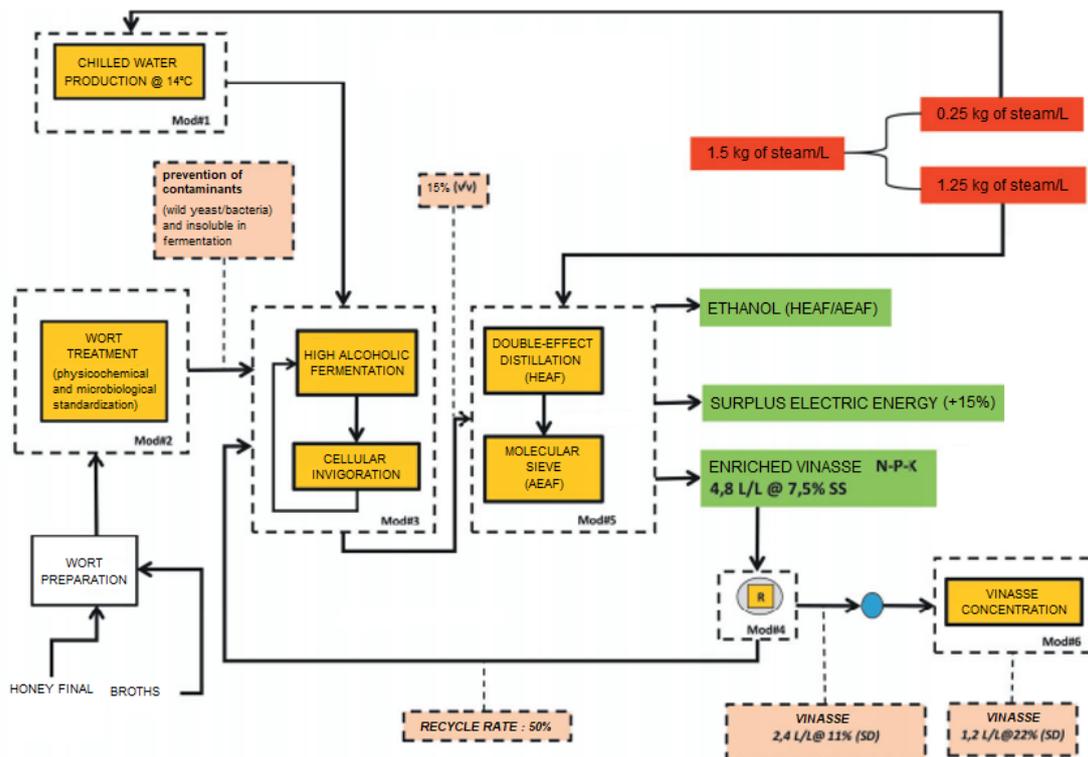


Figure 1. Ethanol Production Chain (NJ Engenharia e Consultoria em Bioprocessos, 2021).

2.2 Biogas

Biogas is the product of the anaerobic biodigestion of vinasse (or other types of biomass), which can be carried out in digesters or reactors. Biogas is an alternative to fossil fuels, because it emits considerably less polluting substances in its combustion process, besides being a way to generate social impact, because it can uncouple the production of energy, whether for urban supply or for locomotion, from the oil business (Silva *et al.*, 2021).

Biogas when originally produced is composed of several substances, but stands out the methane and carbon dioxide

gas, requiring a series of filtering processes to remove the hydrogen sulfide gas, ammonia and water, leaving it ready for combustion (Borges, 2016). According to (Calegari, 2017), the production of methane gas from vinasse generates the effect of decreasing the biochemical oxygen demand (BOD) in ecosystems, an important parameter for the process of depollution of aquatic environments.

2.3 Reactor

Anaerobic digestion is a complex process that has several steps, these are: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Appels *et al.*, 2008), as illustrated in the diagram of Fig. 2 below.

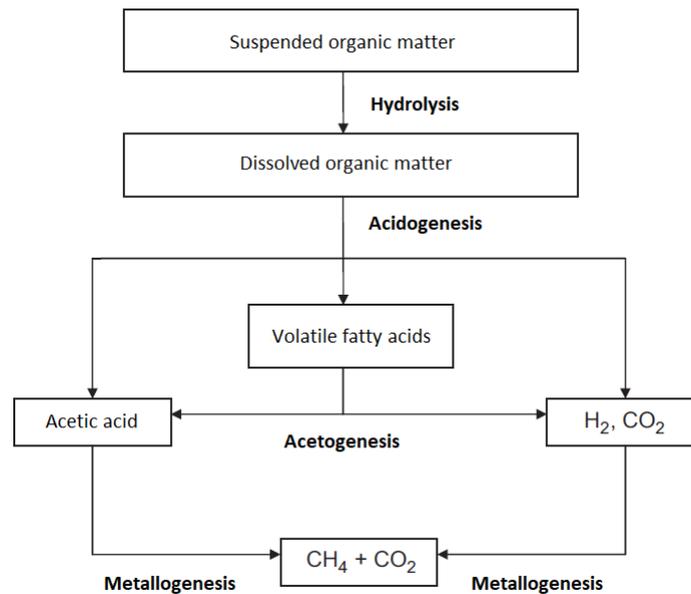


Figure 2. Anaerobic digestion process (Borges, 2016).

Such process occurs within a reactor, which provides a favorable environment for large production of biogas, highlighting the anaerobic reactors of upward flow and sludge blanket (UASB). UASB-type reactors emerged in the Netherlands, but they are widely used in Brazil due to their low cost, operational simplicity, low solid production and because they work well in tropical climates (Borges, 2016).

This type of reactor forms a granular sludge blanket, formed by particular material and microorganisms, suspended in the reactor. The sewage feeds the reactor through the bottom part that crosses the sludge blanket, where the treatment process occurs with the formation of gas bubbles that exit the top part taking several particles with them (Chernicharo, 2007). Figure 3 illustrates the operation of a UASB reactor.

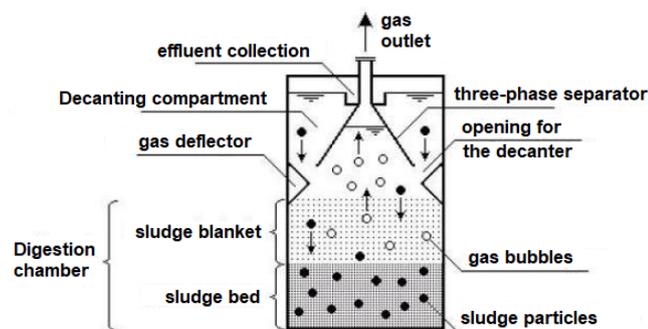


Figure 3. Schematic drawing of a UASB reactor (Chernicharo, 2007).

As mentioned, the UASB reactor has several applications due to its low operating cost. Among these, Table 1 below illustrates the results obtained from the application of the UASB reactor in various segments of the industry.

Table 1. Applications of the upflow anaerobic reactor and sludge blanket-UASB.

UASB Reactor - Residue type and literature	DTT (h)	Temp. (°C)	COD (mg/l)	TSS (mg/l)	Efficiency (%)		Operation Time (days)
					COD	TSS	
Cornstarch Kwong and Fano, 1996.	24-12	37	5,000 5,000		85-89 85-90		510
Domestic sewage with effluent duratex and fleschman Silva <i>et al.</i> , 1995.	6.3-6.9	30	700	780	70	80	730
Molasses (with recirculation) Jhung and Choi, 1995	7.2-3.2	35	2,188	1,952	78		42
Brewery Yan and Tay, 1996	4	21.8	2,030	280	89.1		320
Milk and Sucrose Compound Fang and Chui, 1993	1.8-10	37	12,000			75	200
Hybrid UASB reactor Swine manure Lo <i>et al.</i> , 1994	172 162 79	22-28	6,500 12,000 12,000		95 95 57-61		
Piggery wastewater Oliveira, 1997	12 12 12 12	25 30 25 30	2,932 2,812 3,832 3,709	1,978 1,993 1,493 1,435	82 84 85 87	89 91 84 88	40 38 40 38

Source: Adapted from Carmo Junior (1998)

3. METHODOLOGY

This work was developed through bibliographic research in books, scientific articles, dissertations, theses, and other literature on the subject in order to better understand the production of energy in Brayton and/or Rankine power systems and the use of sugarcane bagasse and biogas from vinasse as fuel in sugar and ethanol plants and about carbon credits.

During the research, a reference work was obtained, (Flausinio, 2015), which deals with sugar and ethanol plants in Minas Gerais, forty-six in operation and fourteen in the design and installation phase, that correspond to the Rankine cycle and utilize sugarcane bagasse as fuel (system I). For one of these plants, undertaking 39, modifications were proposed: in the first analysis, the substitution of sugarcane bagasse by biogas from vinasse; and, in the second analysis, besides this substitution, the implementation of the Brayton cycle, in order to have the Brayton-Rankine combined cycle. Based on the results obtained and assuming 12 hours of operation per day, the original plant was compared with the modified ones.

The analyzed reference presents the boiler operation data and the ethanol production of each mill, which corresponds to 20,000 m^3 of ethanol per day in total. The data for Enterprise 39 are shown in Tab. 2. Since the condemnation pressure is not informed in the analyzed work, a pressure of 15 kPa was considered, based on the SST-300 turbine (Siemens Energy, 2022).

Table 2. Enterprise 39 data provided in the analyzed reference.

Parameter	Value
Bagasse consumed in the boiler	96 ton/h
Installed ethanol production capacity	500 m^3 /day
Boiler steam mass flow rate	200 ton/h
Operating pressure	6.57 MPa
Operating Temperature	520 °C
Turbine efficiency	50%
Efficiency of thermoelectric generation	7.5%

Source: (Flausinio, 2015)

Flausinio (2015) adopted the lower calorific value of sugarcane bagasse equivalent to 7,539 kJ/kg in his calculations. For the production of biogas, the following steps were followed:

The vinasse production was estimated through the Eq. (1) presented below (Poveda, 2019)].

$$Q_v = Q_{et} \cdot F_v \quad (1)$$

In which, Q_v (m^3 vinasse/day) represents vinasse production, Q_{et} (m^3 ethanol/day) is the ethanol production and F_v is the vinasse production factor equals on average 12.5 m^3 vinasse/ m^3 ethanol (Poveda, 2019).

Next, the biogas generation was calculated as a function of the estimated amount of vinasse in a UASB reactor (Eq. 2), whose specifications are given in Tab. 3.

$$PB = Q_v \cdot COD \cdot E \cdot F \quad (2)$$

Where, PB (Nm^3 biogas/day) represents biogas production, COD ($\text{kg COD}/\text{m}^3$ vinasse) is the Chemical Oxygen Demand, E is the COD removal efficiency of the process and F is the biogas conversion factor per COD removed (Nm^3 biogas/ kg COD removed) (Poveda, 2019).

The combustion energy of the biogas was obtained as shown in the equation below:

$$\dot{E}_c = PB \cdot C_{C_{CH_4}} \cdot LHV_{C_{CH_4}} \quad (3)$$

In Eq. (3), \dot{E}_c (kW) represents the combustion energy from biogas, $C_{C_{CH_4}}$ (%) is the methane concentration and $LHV_{C_{CH_4}}$ is the lower calorific value of methane which equals $35713 \text{ kJ}/\text{Nm}^3$ (Okamura, 2013).

Table 3. UASB reactor details.

Parameter	Value
Capacity	75 m^3
COD	$31.8 \text{ kg COD}/\text{m}^3$ vinasse
COD removal efficiency of the process - E	0.72
biogas conversion factor per COD removed - F	0.37 Nm^3 biogas/ kg COD removed

Source: (Poveda, 2019)

The thermodynamic analysis for the proposed plants, as well as the calculation of the biogas production and carbon credits, were performed in the Engineering Equation Solver (EES) software, which has mathematical and thermophysical functions and performs the solution of algebraic equations in order to obtain the installed electric power, the net electric power and the energy efficiency for a comparison analysis between the systems.

In the Rankine cycle with the use of biogas from vinasse (system II), in addition to the boiler operation data and the turbine and thermoelectric generation efficiency of the original plant, the isentropic efficiency of the turbine and pump was considered to be 90%, as well as the pump's efficiency in performing work of the same value.

In the Brayton-Rankine cycle that also uses the biogas from vinasse as fuel (system III), the ideal cycle was adopted for the analysis of the Brayton cycle, which considered air at 27°C and 101.3 kPa at the compressor inlet. The turbine used in the system is the SGT-400, of which the data used in the calculations are shown in Tab. 4. For the steam system, a recovery chair with 86% efficiency and operating pressure and temperature equivalent to the original plant's boiler was adopted, in addition to a condensing pressure of 15 kPa .

The efficiency of the electric generators, turbines, compressor and pump was also considered to be 95% and the isentropic efficiency of the turbines, compressor and pump to be 90%. The mass of steam was obtained as a function of the heat transferred to the water in the boiler and the thermodynamic states at the boiler outlet and inlet.

Table 4. Model SGT-400 Gas Turbine.

Air mass flow rate	44.5 kg/s
Pressure ratio	18.5
Exhaust gas temperature	$529 \text{ }^\circ\text{C}$

Source: (Siemens Energy, 2020)

3.1 Carbon credits

The carbon production in the combustion of the fuels in each system was calculated from the following equation, in order to verify which systems produced less carbon dioxide and, consequently, carbon credits.

$$BLE = \frac{V \cdot CC \cdot R_{CO_2/C}}{1000} \quad (4)$$

In Eq. (4), $BLE (t_{CO_2/h})$ represents the baseline emissions, V is the bagasse or vinasse flow (kg/h or m^3/h , respectively), CC is the carbon concentration in bagasse or vinasse (kg/kg or kg/m^3 , respectively) and $R_{CO_2/C}$ responds for being the atomic mass ratio CO_2/C equals 3.67 (Szymanski *et al.*, 2010).

According to Rafaldini *et al.* (2006), the carbon concentration in vinasse corresponds to $3 kg/m^3$ and, as reported by Segundo (2014), 46% in sugarcane bagasse.

4. RESULTS AND DISCUSSION

From the $20,000 m^3$ ethanol/day production of the plants, it is estimated that the biogas production in UASB reactors, according to the adopted specifications, is equivalent to $2.11 \times 10^6 m^3$ of biogas/day, which corresponds to a combustion energy potential of approximately 525 MW. For the cycles of systems II and III, by EES, the respective T-s diagrams were obtained. They are presented in Fig. 4 and Fig. 5 as well as the thermodynamic states after each process of the cycle, which are shown in Tab. 5 and Tab. 6, respectively.

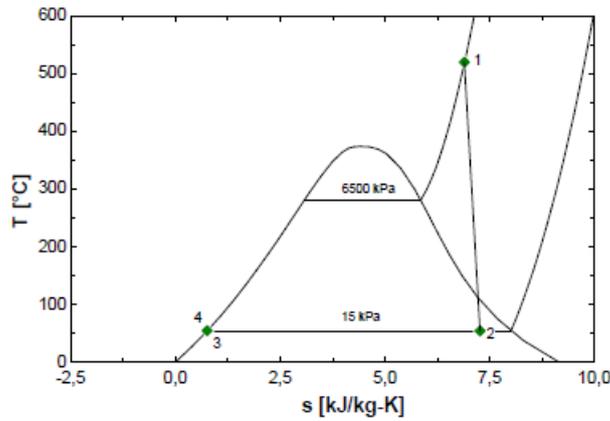


Figure 4. System II T-s diagram.

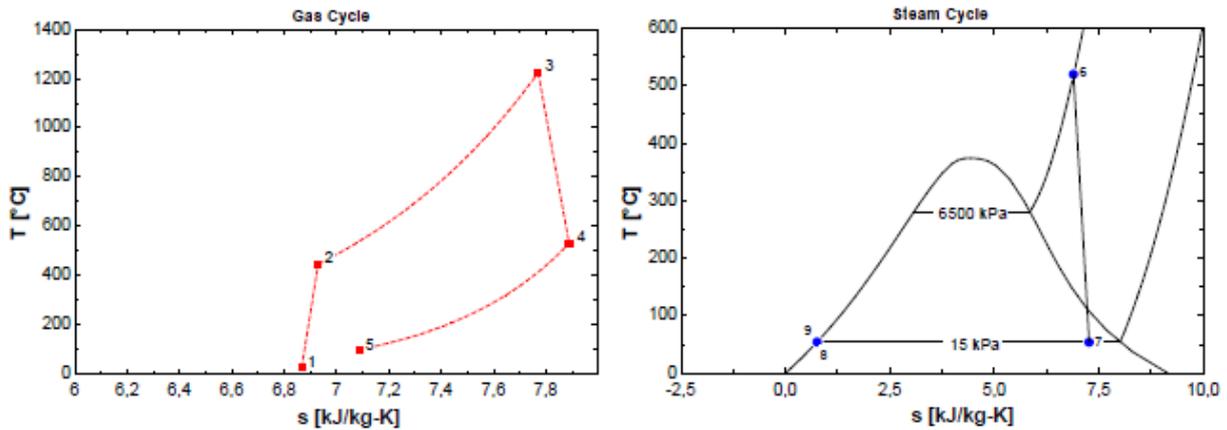


Figure 5. System III T-s diagrams.

Table 5. Thermodynamic states of the system II.

Point	Temp. (°C)	Pressure (kPa)	Enthalpy (kJ/kg)
1	520	6,570	3,464
2	53.98	15	2,357
3	53.98	15	226
4	54.41	6,570	233.4

Source: Authors

Table 6. Thermodynamic states of the system III.

Point	Temp. (°C)	Pressure (kPa)	Enthalpy (kJ/kg)
1	27	101.3	300.5
2	446.6	1,874	735.4
3	1,224	1,874	1,634
4	530.3	101.3	826.4
5	100	101.3	374.1
6	520	6,570	3,464
7	53.98	15	2,357
8	53.98	15	226
9	54.41	6,570	233.4

Source: Authors

The value obtained for the steam mass flow rate in system III corresponds to 6.23 kg/s. For the considerations and analyses admitted, the results presented in Tab. 7 and Fig. 6 were also obtained.

Table 7. Systems specifications.

System	Thermodynamic Cycle	Fuel	Fuel Consumption
I ⁽¹⁾	Rankine	Sugarcane Bagasse	96 ton/h
II	Rankine	Biogas from Vinasse	33,777 m ³ /h
III	Brayton-Rankine (Cogeneration)	Biogas from Vinasse	6,720 m ³ /h

⁽¹⁾ For Enterprise 39

Source : Authors

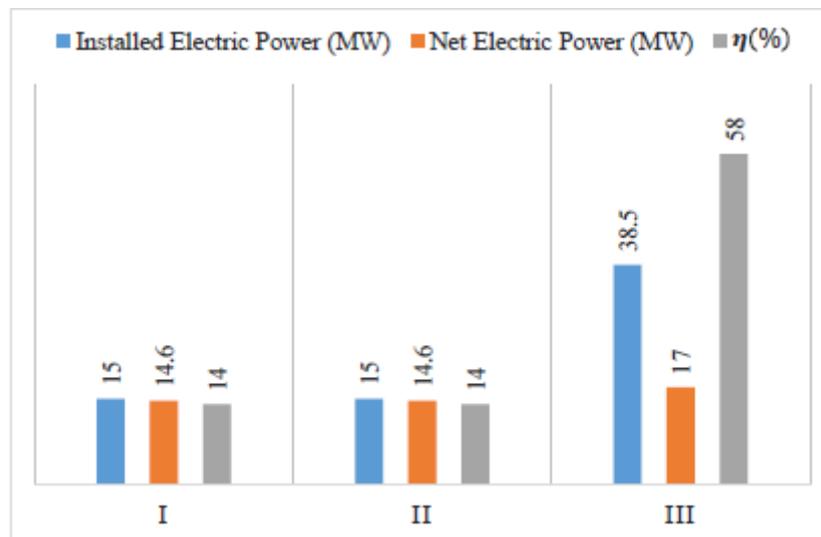


Figure 6. Electric Power and efficiency (η).

Enterprise 39 has the capacity to supply 4,412 m³ of biogas/hour, so it will require an additional 29,365 and 2,308 m³ of biogas/hour in systems II and III, respectively, that can be supplied by the other plants.

When comparing the systems, it was observed that systems I and II have the same performance and the distinction lies in the type of fuel used; system III presents a 13.3% increase in net electric power in relation to the other systems, despite using less fuel, which occurs because this system is a combined cycle cogeneration system and has very efficient components.

4.1 Thermal energy for soaking

In the condensation process, 112 MW of thermal energy is rejected in systems I and II, while in system III this rejection corresponds to 13 MW. This energy can be used in the soaking process in sugar and ethanol plants, which consists of using

hot water (around 80°C) with the objective of increasing the dilution of the juice and increasing juice extraction in the suit, besides avoiding the development of microorganisms (Vilela, 2013).

4.2 Results for carbon credit analyses

Analyzing the quantity of fuel consumed in the systems, by the results presented in Tab. 8, it was verified that although the systems I and II produce the same quantity of combustion energy, system II presents 72.9% of reduction in the carbon composition in the fuel in comparison with system I, so that it generates 118 carbon credits per hour. While as system III requires less energy, so that the reduction of carbon in the reactant is due to both having a lower carbon composition than sugarcane bagasse for the same amount of combustion energy, and the requesting amount of biogas consumption being less, there is the production of 153 and 35 carbon credits per hour compared to systems I and II, respectively. Therefore, the use of biogas as an energy source enables the production of carbon credits.

Table 8. Avoided emissions of systems II and III compared to system I.

System	Carbon Composition (kg _{CARBON} /h)	Baseline Emissions (t _{CO2} /h)	Avoided Emissions (t _{CO2} /h)
I	44,160	162.1	-
II	11,961	43.9	118.2
III	2,360	8.7	153.3

Source: Authors

5. CONCLUSION

From the thermodynamic analysis of the enterprise 39 and the systems with the proposed modifications, it was found that, for the specifications of the systems analyzed, the combined cycle system (Brayton-Rankine) consisting of high efficiency components is more efficient than the Rankine cycle system, even though it requires less combustion energy in relation to the other systems.

It was also verified, by evaluating the production of carbon dioxide in the consumption of fuels by the systems, that the use of biogas from vinasse (systems II and III), in comparison with sugarcane bagasse (system I), generates carbon credits, even though the combustion energy of biogas is equivalent to that of bagasse.

In addition, there is the possibility that the thermal energy rejected in the condensation process in the systems can be reused in several ways, such as in the heating of water for industrial processes, which is a utility demanded in the sugarcane mills by the soaking process.

In this way, energy production in thermoelectric plants can be cleaner and generate less environmental impact with the reuse of waste for the generation of biofuels; as seen, the vinasse for the production of biogas, as well as having more efficient systems, such as those of cogeneration and combined cycle, also contribute to this.

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