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ENERGETIC AND ECONOMIC ANALYSIS OF THE BIOHYDROGEN PRODUCTION USING BIOGAS FROM VINASSE IN THE SUGAR CANE INDUSTRY

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Abstract. *In this paper is study the potential of bioelectricity generation from vinasse biogas, to feed a water electrolyser to obtain biohydrogen. Is analyzed the production capacity of bioelectricity using the vinasse biogas in a internal combustion engine set Caterpillar CG 260-16 (60Hz) model. By the energy analysis of biohydrogen production, and energy efficiency determination of the process is possible the construction of the Sankey Diagram of the process. To study the electrical energy production potential, real production data from a sugar cane plant located in the state of São Paulo are used. The electrolyser used is the HySTAT 600 model, chosen by the minimum electrical power required for its operation. In the next step the cost of biohydrogen production by electrolysis using vinasse biogas from the sugar/alcohol industry of Brazil is determined as a function of payback period, operation hours and annual interest rate. Also, its economic feasibility is studied of the biohydrogen production process. As the conclusion, are demonstrate the efficiency level of bioelectricity generation and biohydrogen production.*

Keywords: *Hydrogen, Biogas, Vinasse, Electrolysis, Energetic Analysis, Economic Analysis*

1. INTRODUCTION

In recent years, there has been an increasing demand for sustainable energy sources, driven by the exhaustion of oil and natural gas reserves. Countries with significant resource generation infrastructure are actively seeking solutions that minimize or eliminate greenhouse gas emissions. Brazil, as a global leader in sugar cane production, exemplifies this trend. With a vast land area of 850 million hectares, nearly 1% is dedicated solely to sugar cane cultivation. Remarkably, sugar cane yields are impressive, with potential production reaching up to 72 tons per hectare (Belicanta et al., 2016).

The Brazilian sugar and alcohol industry extends beyond sugar production, sugar sales represent 53% of the total profits. Additionally, ethanol contributes with 42% to the profits, and electricity sales comprise the remaining 2% (Goes et al., 2008). Also, they use vinasse, a derivative of the distillation of ethanol, as a fertilizer and to obtain a 2nd generation ethanol. In fact, the sugar and alcohol industry in Brazil has a great potential for electricity generation.

Industrial processes often generate harmful waste that, if it is not properly managed, can have harmful effects on soil, water sources, and contribute to increased greenhouse gas emissions, thereby causing environmental contamination. Vinasse is one of this type of waste, it is recognized as the primary pollutant derived from ethanol production, representing a persistent and difficult-to-treat wastewater (Parsaee et al., 2019). But in other hand, vinasse is also a type of biomass, approximately 75% of its composition is organic matter (Pereira et al., 2020). This organic matter includes non-fermentable substances like glucose and fructose, as well as fermented byproducts that remain after distillation, such as glycerol, organic acids, and residual yeast (Tadeu and Zaiat, 2018).

The anaerobic digestion method is highly effective for vinasse treatment, particularly on a large scale. Thanks to its composition and high organic matter content, vinasse represents a highly viable feedstock for biogas production (Prenzier et al., 2011). Biogas is produced through the fermentation of organic materials, in which the environment is in lack of

oxygen. This method involves the biological conversion of complex organic components into various chemicals, including methane, carbon dioxide, ammonia, and water. During this process, sulfates and a significant portion of the organic matter are removed, and volatile components and essential nutrients can be separated (Budiyono and Syaichurrozi, 2014). Consequently, the sulfur content in vinasse can be reduced to less than 1%, which is crucial for biogas production. High concentrations of sulfur can lead to the formation of hydrogen sulfide (H_2S), which negatively impacts biogas formation (Velásquez et al., 2019). The primary component of biogas is methane (CH_4), from 50% to 75% in concentration. The remaining consists of carbon dioxide (CO_2) from 25% to 48%, along with minor quantities of other gases.

Vinasse exhibits a high concentration of solids and a significant Chemical Oxygen Demand (COD). COD represents the amount of oxygen required to chemically break down organic matter. Organic materials with a high COD content can be transformed into biogas through microbial activity in anaerobic digesters (Parsaee et al., 2019). The total solids (TS) content in stillage can vary based on different references, with some indicating a range of 63,000 to 79,000 mg/L, while others suggest a value of 100,000 mg/L (Syaichurrozi, 2016). In fact, vinasse can contain even higher levels, reaching up to 299,250 mg/L (Budiyono and Syaichurrozi, 2014). Due to these substantial amounts, vinasse should not be discharged into water bodies such as rivers or seas, as its high COD content can deplete the oxygen concentration, posing a threat to aquatic organisms and ecosystems (Syaichurrozi, 2016).

Now to produce biohydrogen through water electrolysis it is required an electric current passing to an electrolytic conductor, such as alkaline, polymeric, or solid oxide materials. This process leads to the splitting of water molecules into biohydrogen (H_2) and oxygen (O_2) (Santos and Sequeira, 2019). The anode facilitates the oxidation reaction, resulting in the release of oxygen from water. The cathode facilitates the reduction reaction that captures hydrogen from water. Consequently, this process yields biohydrogen with significant energy potential. Notably, the biohydrogen produced via this method exhibits high purity as it does not generate carbon, sulfur, or nitrogen compounds (Ju et al., 2018)

This study focuses on exploring the potential for generating green hydrogen using the electrolysis method in an electrolyser. The electrolyser is powered by bioelectricity derived from the combustion of vinasse biogas. Several aspects are investigated in this work. Firstly, the research examines the potential for electricity generation based on the annual ethanol production of a sugar cane plant, calculations are performed to determine the amount of electricity that can be generated using a motor/generator set (Arruda et al, 2019). Lastly, the cost of producing biohydrogen is calculated conducting a technical and economic analysis of the results to evaluate the overall feasibility of the process. By analyzing these aspects, the study aims to provide insights into the technical and economic viability of generating biohydrogen through the proposed approach (Pereira et al., 2020).

2. OBJECTIVES

The main objective of this study is to conduct a comprehensive technical and economic analysis of biohydrogen production using bioelectricity obtained from vinasse biogas. Also are specific objectives:

- Study the potential for bioelectricity generation from stillage biogas.
- Learn the process of electrolysis of water operating with bioelectricity.
- Study the energy efficiency of bio hydrogen production.
- Determination of the bioelectricity and biohydrogen production costs.

3. METHODS

The system that is proposed for this paper is to use a set between an internal combustion engine running on vinasse biogas and an electricity generator, in which it is study its bioelectricity production. Then this motor/generator set will be connected to an electrolyser to evaluate the production of bio-hydrogen. As a case of study, first the biogas generation potential of a sugar cane plant in the São Paulo state will be analyzed, taking data the harvest 2022/2023 until April 2023 (Conab, 2023). Then it is calculated its bioelectricity generation potential using the Motor/Generator set and the biohydrogen production with electrolysis, to later carry out the energy and economic analysis.

3.1 Vinasse biogas production potential and Energy power supplied by the sugar cane plant selected.

The quantity of vinasse produced can vary among ethanol producers but for this study, a value of 12 m³ of vinasse per liter of ethanol was chosen (Cassman et al., 2018). Under standard conditions of 0°C and 1 atm, it has been found that 1 gram of COD can produce 0.35 liters of methane gas. Therefore, at 35°C and 1 atm, 1 gram of COD can yield 0.395 liters of methane gas. Consequently, 10 to 26.4 m³ of biogas, containing 60% methane, can be generated from 1 m³ of vinasse (Parsaee et al. 2019).

The "Usina São Jose da Estiva" was selected to make the studies. It is in the municipality of Novo Horizonte, which in the 2022/2023 harvest, registered an ethanol production of 180.000,00 m³ (Conab, 2023). Obtaining the biogas flow rate, it is only necessary convert the production in m³/year of ethanol into m³/hour of biogas. For this plant, this value corresponds about to 2,465.7535 m³/h. To calculate the energy power supplied by the fuel, E_{fuel} , in kilowatts (kW), it is

used the Low Heat Value (LHV) of typical vinasse biogas, $LHV_{fuel} = 23 \text{ MJ}/\text{m}^3$, and the specific mass of Biogas, $M_{biogas} = 18428 \text{ kg}/\text{m}^3$ to convert the dimensions of the biogas flow rate into (kg/s), obtaining the mass flow of the fuel, m_{fuel} (kg/s) (Wendling, 2020). The energy power supplied can be obtained using Eq. (1):

$$E_{fuel} = m_{fuel} * LHV_{fuel} \quad (1)$$

3.2 Energetic analysis.

A. Energy balance of the motor/generator set for bioelectricity generation process.

For the bioelectricity process, is used an internal combustion engine together with an electricity generator running with vinasse biogas, the inputs and products of the process are presented in Figure 1.

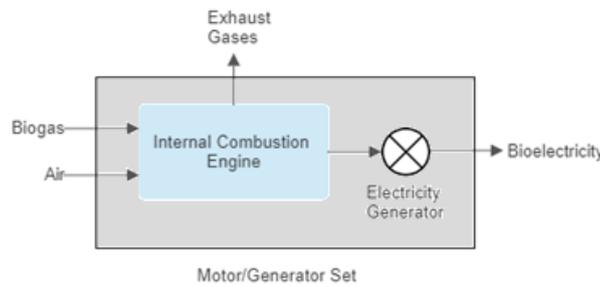


Figure 1: Flowchart of the bioelectricity process

The selected motor/generator set for bio-electricity production in the electrolysis process is the CG260-16 model by Caterpillar (Caterpillar, 2023). This model is versatile, capable of utilizing various fuel sources such as natural gas, biogas, coal gas, and synthesis gas. The key specifications and features of the CG260-16 model are provided in Table 1:

Table 1. specifications and characteristics of the CG260-16 model.

Characteristics	Value
Electric Power (using Biogas) [kW]	3510
Frequency [Hz]	60
Electrical efficiency [%] η_{eICM}	43,2
Thermal efficiency [%]	38,5

The bioelectricity produced, E_{pICM} (kW), can be calculated by Eq. (2) (Wendling, 2020):

$$E_{pICM} = \eta_{eICM} * E_{fuel} \quad (2)$$

To begin, it is considered the first law of thermodynamics, the law of conservation of energy, to carry out the energy balance, using Eq. (3) (Arruda et al., 2019). Since there is no cogeneration for the proposed case, Eq. (3) is rewritten as Eq. (4), considering a single thermal power variable, E_{STP} , for engine cooling, E_{ec} , and exhaust gases, E_{eG} (Picón et al., 2022) everything in (kW):

$$E_{fuel} + m_{air}h_{air} = E_{pICM} + E_{ec} + E_{eG} + Losses \quad (3)$$

$$E_{fuel} + m_{air}h_{air} = E_{pICM} + E_{STP} + Losses \quad (4)$$

For the losses, it is recommended that they can be estimated with an 8% of the total energy supplied by the fuel (Wendling, 2020).

B. Energetic analysis of the electrolysis process for biohydrogen production process.

For the biohydrogen process, the bioelectricity produced by the motor/generator set runs the electrolyser, where the process of electrolysis will begin. The inputs and products of the process are presented in Figure 2:

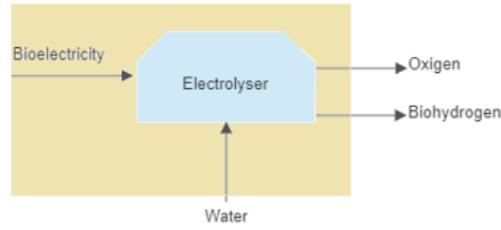


Figure 2: Flowchart of the electrolysis process for biohydrogen production.

The electrolyser HySTAT 600 model from Hydrogenics was chosen, with its specification shown in Table 2:

Table 2: HySTAT 600 specifications

Characteristics	Value
Capacity [Nm ³ /h]	600
Electric power [kW]	2940
Water consumption [m ³ /h]	1,05

The energy efficiency of the electrolyser, $\eta_{electrolyzer}$ (-), is determined with the data in Table 2 and Eq. (5):

$$\eta_{electrolyzer} = \frac{\dot{m}_{H_2} * LCV_{H_2}}{E_{required}} \quad (5)$$

To calculate the power supplied by the hydrogen produced, \dot{E}_{H_2} (kW), it can be calculated with Eq (6):

$$\dot{E}_{H_2} = \dot{m}_{H_2} * LCV_{H_2} \quad (6)$$

The mass flow of hydrogen produced, \dot{m}_{H_2} (kg/s), is cleared from the Eq. (5), obtaining Eq. (7):

$$\dot{m}_{H_2} = \frac{\eta_{electrolyzer} E_{required}}{LCV_{H_2}} \quad (7)$$

Through Eq. (8) it is possible to determine the amount of biogas necessary, $\dot{m}_{biogasICM}$ (kg/s), to produce the electrical power obtained from the motor/generator set (Paulino et al., 2016):

$$\dot{m}_{biogasICM} = \frac{E_{pICM}}{\eta_{eUICM} * LCV_{biogas}} \quad (8)$$

C. Energetic analysis of the complete system (bioelectricity and biohydrogen production process).

The complete system is represented through the Figure 3:

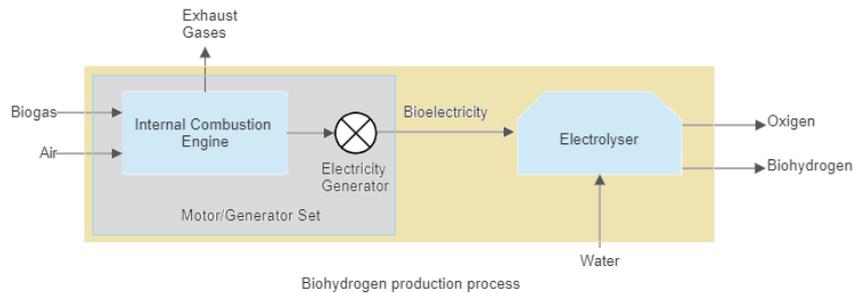


Figure 3: Flowchart of the biohydrogen production process using the bioelectricity made by the motor/generator set.

The energy efficiency of the whole process, $\eta_{elec.eUICM}$ (-), the electrolyser is connected with the motor/generator set burning vinasse biogas, so its efficiency is calculated using Eq. (9) (Silveira et al., 2014):

$$\eta_{elec.eUICM} = \eta_{electrolyzer} * \eta_{eUICM} \quad (9)$$

3.3 Economic analysis.

A. Economic analysis of the bioelectricity generation process

To calculate the annuity factor, f (-), it is using Eq. (10):

$$f = \frac{q^k * (q-1)}{q^k - 1} \quad (10)$$

Where $q = 1 + \frac{i}{100}$, with i being the annual interest rate (%), values of 4%, 8%, and 12%. And the value k is the payback period, where a time equivalent of 25 years was chosen.

To determine the production cost of bioelectricity from the motor/generator set, C_{eUCM} (US\$/kWh) was used Eq. (11) (Silveira et al., 2014), and some fixed parameters shown in Table 3:

$$C_{eUCM} = \frac{I_{pICM} * f}{H * E_{pICM}} + C_{fuel} \frac{E_{fuel}}{E_{pICM}} + C_{mICM} \quad (11)$$

Table 3: Fixed parameters for the calculation for the investment cost of the motor/generator set.

Maintenance cost of the motor/generator set C_{mICM}	0.015 US\$/kWh
Cost of fuel C_{fuel}	0,019 US\$/kWh
Working period H	7300 h

The investment cost of the motor/generator set, I_{pICM} (US\$), is calculated using the Boehm methodology, in which the investment cost of implementing the plant can be estimated using Eq. (12) (Kumar and Himabindu, 2019):

$$C = C_R * \left(\frac{s}{s_R}\right)^m \quad (12)$$

With it, it is possible to estimate the investment cost of the implementation of the plant from Figure 4, obtaining Eq. (13), for an electric power range between 400 and 4300 kW (Pauline et al., 2016).

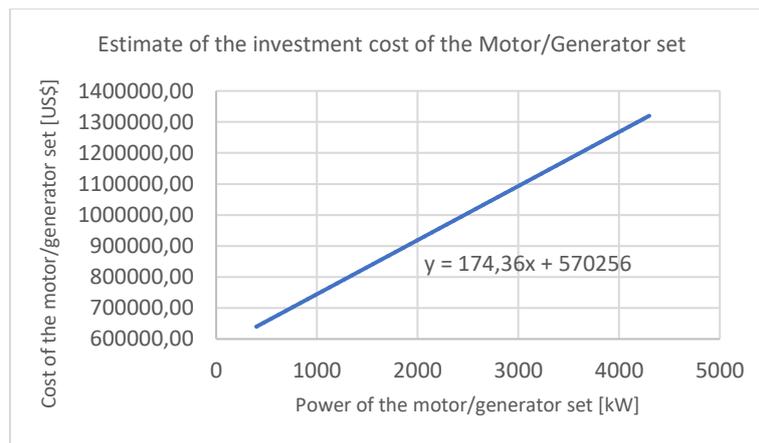


Figure 4: Methodology for determining the investment cost for the motor/generator set.

$$I_{pICM} = 174,36 * E_{ICM} + 570256 \quad (13)$$

B. Economic analysis of the bio hydrogen generation process (electrolysis process fed with bioelectricity).

The analysis is the same as for the electricity production process. The objective is to determine the cost of producing biohydrogen from the electrolysis process, so some calculations vary. $C_{H_2electrolysis}$ (US\$/kWh) is calculated by Eq. (14):

$$C_{H_2electrolysis} = \frac{I_{electrolyzer} * f}{H * \dot{E}_{H_2}} + C_{op_{electrolyzer}} + C_{man_{electrolyzer}} \quad (14)$$

Eq. (15) allows calculating the operating cost of the electrolyser, $C_{op_{electrolyzer}}$ (US\$/kWh), this equation will need some parameters found in literature shown in Table 4:

$$C_{op_{electrolyzer}} = \frac{\dot{E}_{req} * C_{elUCM}}{\dot{E}_{H_2}} + \frac{\dot{m}_{H_2O} * C_{H_2O}}{\dot{E}_{H_2}} \quad (15)$$

Table 4: Parameters used for the operation cost of the electrolyser.

Power required by the electrolyser \dot{E}_{req}	2940 kW
Power supplied by biohydrogen \dot{E}_{H_2}	1248,598 kW
Water rate for industrial process C_{H_2O}	0,00256 US\$/kg
Mass flow of water in the electrolyser \dot{m}_{H_2O}	0,83295 kg/h

The cost of electrolysers, $C_{electrolyzer}$ (US\$), for the biohydrogen production range from 0.1 kg/h to 100 kg/h can be estimated with Eq. (16) (Paulino et al., 2016):

$$C_{electrolyzer} = 224,49 * (\dot{m}_{H_2})^{0,6156} * 10^3 \quad (16)$$

This equation allows an estimation of the investment cost for an electrolyser equipment. It is considering a production capacity of 100 Nm³/h and other one of 1000 Nm³/h, Results are shown in Table 5:

Table 5: Estimated cost of the electrolysers using Eq. (16)

Electrolyser Capacity	Biohydrogen flow rate	Estimated cost of the electrolyser
100 Nm ³ /h	8,99 kg/h	867.623,82 US\$
1000 Nm ³ /h	89,9 kg/h	3.580.399,32 US\$

The Boehm method is employed with these values, obtaining Figure 5 and Eq. (18), to determine the investment cost of the electrolyser $I_{electrolyzer}$ (US\$)

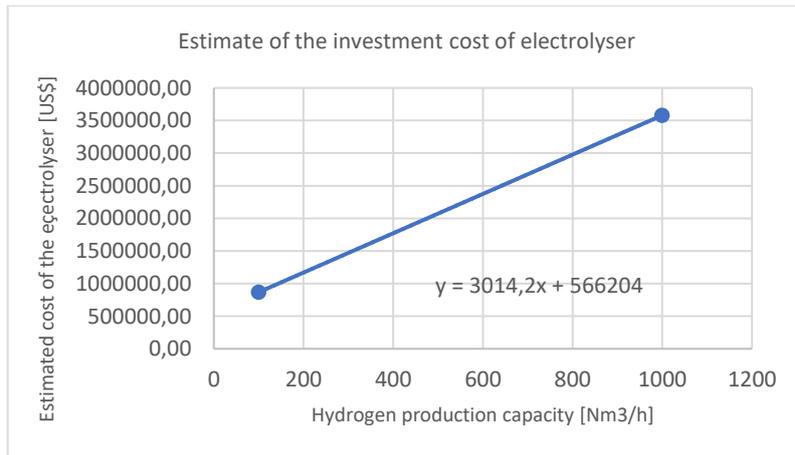


Figure 5: Methodology for determining the investment cost for the electrolyser.

$$I_{electrolyzer} = 3014,2 * P_{H_2} + 566204 \quad (18)$$

The maintenance cost of the electrolysis process $C_{man_{electrolyzer}}$ (US\$/kWh), is the 3% of the investment cost of the plant, Eq (19) (Picón et al., 2022):

$$C_{manelectrolyzer} = 0,03 * \frac{I_{electrolyzer} * f}{H * \dot{E}_{H_2}} \quad (19)$$

To determine the projected annual income of the biohydrogen production system, R_{H_2} (US\$/year) it is used Eq. (20) and the parameters shown in Table 6:

$$R_{H_2} = [E_{pICM} * H * (C_{ele} - C_{elICM})] + [\dot{E}_{H_2} * H * (C_{H_2} - C_{H_2electrolyser})] \quad (20)$$

Table 6: Fixed parameters for the calculation of the projected annual income.

Sale price of biohydrogen	0,1358 US\$/kWh
Period of equivalent use of the system	7300 h
Cost of electricity	0,11 US\$/kWh

4. RESULTS

4.1 Results of the energetic analysis Results of the vinasse biogas production potential and energy power supplied by the sugar cane plant selected.

In Table 7 it is shown de energy potential generation of the ethanol plant selected.

Table 7. Biogas flow rate of biogas and energy potential generation

Ethanol Plant	Vinasse production	Daily production of biogas	Biogas flow rate	Mass flow of Biogas	Energy potential generation
São José da Estiva	5.917,808 m ³ /day	59.178,082 m ³ /day	2.465,7534 m ³ /h	1,2621 kg/s	15.753,425 kW

The energy potential is very high because it is above 10MW, which makes it unlikely to find a set capable of using the full load of the plant. Therefore, when using biogas in power generation, ranges from a few to several hundred kW are used (Prenzier et al., 2011). If now only 30% of the total energy potential is used to feed the generator set, it is obtained a value more suitable for its implementation in a motor/generator set. Result is shown in Table 8:

Table 8. Energy power supplied by the fuel using only the 30% of total ethanol production.

Ethanol Plant	Energy potential (30%)
São José da Estiva	4.726,027 kW

4.2 Results of the energetic analysis.

A. Results of the energy balance of the motor/generator set for bioelectricity generation process.

The theoretical bioelectricity than can be produced by the plant is shown in Table 9, and the results of the energy balance of the system is shown in Table 10 and Figure 6, respectively.

Table 9. Theoretical Bioelectricity produced by the motor/generator set using the fuel supplied by the plant.

Ethanol Plants	Bioelectricity produced
São José da Estiva	2.041,6438 kW

Table 10: Energy balance of the biohydrogen production process.

Energy balance	
E_{fuel}	4.726,0274 kW
E_{pICM}	2.041,6438 kW
E_{STP}	2.521,052 kW
Losses	163,3315 kW

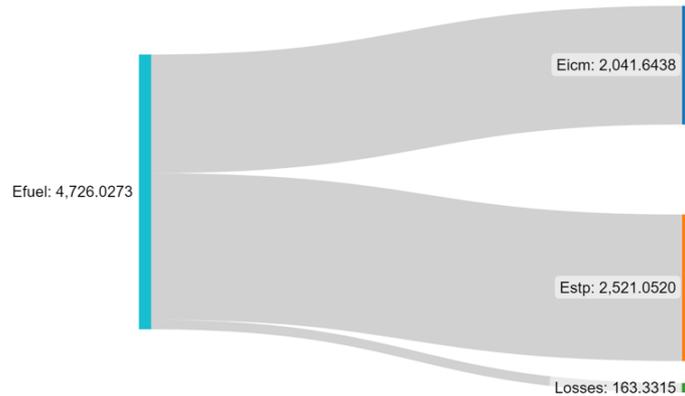


Figure 6. SANKEY diagram of the energy balance of the motor/generator set.

B. Results of the energy balance of the electrolysis process for biohydrogen production process.

The energy efficiency of the electrolyser and other parameters obtained are shown in Table 11, the power supplied by the biohydrogen is shown in Table 12, and the mass flow of biogas is shown in Table 13.

Table 11: Energy efficiency of the electrolyser.

Electricity required in the electrolyser [kW].	2940
Lower calorific value of biohydrogen [kJ/kg].	120000
Mass flow of biohydrogen produced [kg/s].	0,01498
Energy efficiency of the electrolyser [%]	61,16

Table 12: mass flow of biohydrogen and energy power supplied by de bio hydrogen production for the São José da Estiva plant.

Ethanol Plant	Mass Flow of bio hydrogen	Power supplied by biohydrogen
São José da Estiva	0,010405 kg/s	1248,598 kW

Table 13: Mass flow of biogas from the Sao Jose da Estiva plant.

Ethanol Plant	Mass flow of biogas	Mass flow of biogas
São José da Estiva	0,30631 kg/s	480,84 Nm ³ /h

C. Energy efficiency of the complete system (bioelectricity generation with biohydrogen production).

The energy efficiency of the whole process considering the motor/generator set and the electrolyser it is shown in Table 14.

Table 14: Energy efficiency of the whole process

Electric efficiency CG260-16 model	43,2 %
Electric efficiency HySTAT 600	61,15 %
Electric efficiency of the system	26,42 %

4.3 Results of the economic analysis.

A. Economic analysis of the bioelectricity generation process

E_{ICM} in Eq (13) correspond to the power capacity of the motor/generator set selected, the CG260-16, with a value of 3510 kW. Making possible to obtain the investment value in dollars of the equipment, shown in Table 15.

Table 15: Investment value for the motor/generator set.

Ethanol Plant	Motor/generator set	Electrical power	Investment
São José da Estiva	Caterpillar CG260-16	3510 kW	1.182.259,6 US\$

With all the calculations made, it is possible to obtain the cost of the electricity produced by the motor-generator set, fed by the São José da Estiva plant shown in Figure 7.

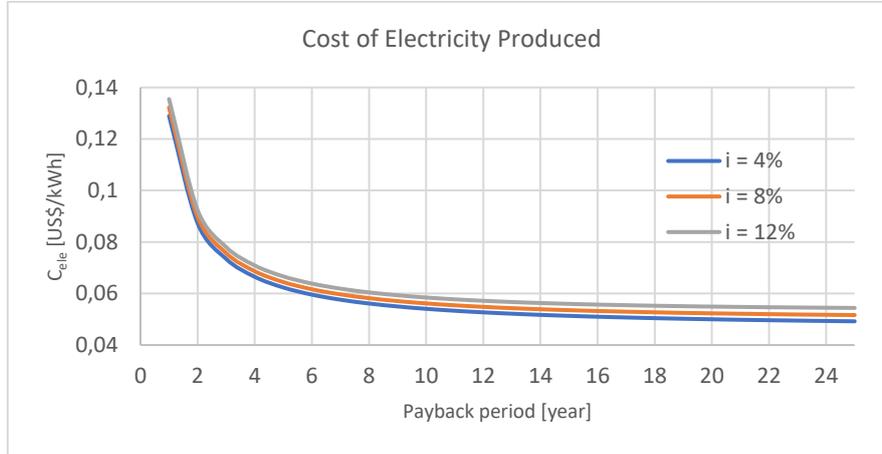


Figure 7: cost of electricity of the São José da Estiva plant in a term of 25 years.

B. Economic analysis of the biohydrogen production process

The model chosen was the HySTAT 600 from Hydrogenics, with a P_{H_2} of 600 Nm³/h. if this value is replaced in Eq (19), the investment cost from the electrolyser is shown in Table 16:

Table 16: Investment cost for the electrolyser HySTAT 600.

Electrolyser Capacity	Biohydrogen flow rate	Estimated cost of the electrolyser
600 Nm ³ /h	53,255 kg/h	2.374.724,00 US\$

The cost of biohydrogen production based on a period of 25 years of the implementation of the system is shown in Figure 8, and the expected annual income based on the payback method is shown in Figure 9.:

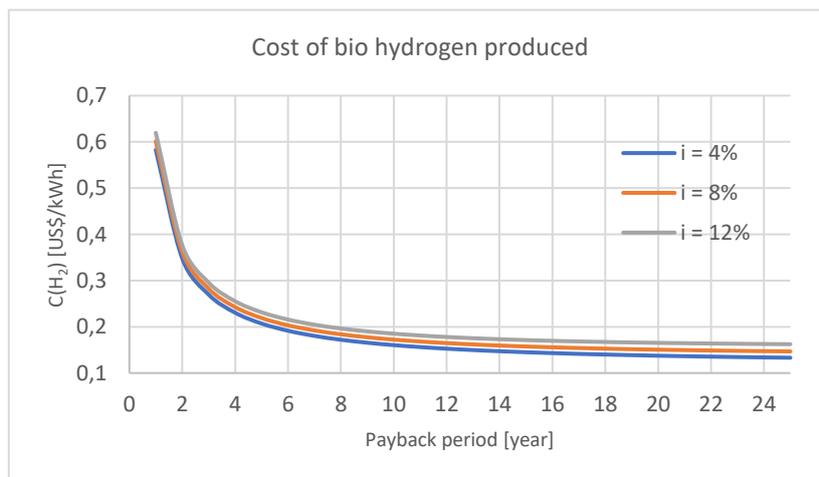


Figure 8: cost of produce bio-Hydrogen by the São José da Estiva plant in a term of 25 years

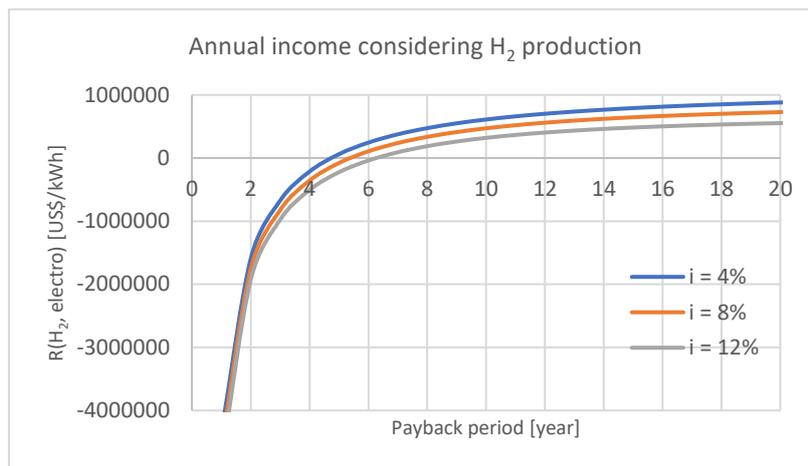


Figure 9: expected annual revenue from the production of Bio-Hydrogen using the motor/generator set with the power supplied by the São José da Estiva plant.

5. CONCLUSIONS

From the energy analysis, it can conclude that, by taking a smaller portion of the ethanol production from the plant, it is possible to generate bioelectricity and take advantage of more than 40% of it to feed the electrolyser, and this in turn, having a high efficiency, it is possible to have it running 7300 hours a year.

Regarding the economic analysis, first it was not considered that most of the sugar plants generate their own electricity from cogeneration, and the analysis was carried out only considering the energy production of the motor/generator set. Taking annual interest rates ranging from 4, 8 and 12%, throughout the 25 years that were considered for this analysis, as shown in figure 7, the cost of producing bioelectricity went from the range of 0.128 US\$/kWh and 0.135 US\$/kWh in the first year of system implementation to a stable range between 0.063 US\$/kWh and 0.595 US\$/kWh in its first 5 years, reaching a minimum price range of 0.049 US\$/kWh and 0.054 US\$/kWh at the end of the 25-year period. In figure 8, the cost of producing biohydrogen is high at the beginning, since it starts in a range of between 0.583 US\$/kWh and 0.619 US\$/kWh in the first year of use of the system. However, the price falls by almost half in the second and third year of use reaching a price in the range of 0.156 US\$/kWh and 0.181 US\$/kWh in its first 10 years, a decrease of almost 0.5 US\$/kWh in that period. Taking into consideration that the current cost of green hydrogen is 0.253 US\$/kWh, there is a profit of \$0.07 US comparing the cost of producing biohydrogen in the industry to the cost of producing the same with this system. With figure 9, the value for the amortization period of the capital invested in the system is between 5 and 6 years (interest rate 4% and 12% respectively). In this range, annual income of between 319,647.20 US\$/kWh and 610,516.30 US\$/kWh is expected in the first 10 years. Reaching almost one million US\$/kWh per year, at the end of 25 years.

Finally, the process of obtaining biohydrogen by electrolysis, using only 30% of the total stillage production of the São José da Estiva plant, is a viable investment in the medium and long term. Even without considering the electricity generated by the same plant. In future works, the implementation of the system will be evaluated, but now considering the cogeneration energy of the plant itself, where it is inferred that the costs of generating energy and bio hydrogen, as well as the return value of the investment, will result considerably better for the plant that decides to implement this system.

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