



Article

Technical and Economic Analyses for the Implementation of a Biohydrogen Production System Using Bioelectricity from Vinasse Biogas of the Sugarcane and Alcohol Industry

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Abstract: This paper studies the implementation of a system consisting of an electrolyzer connected to a bioelectricity generator set that operates using vinasse biogas. Data on total ethanol production across all regions of Brazil were collected, and two ethanol plants in São Paulo state were selected for analysis (São Jose da Estiva and São Manoel). The feasibility of implementing this system at these facilities was evaluated using energy analysis for biohydrogen production. The process's energy efficiency was assessed, allowing for the construction of a Sankey Diagram for both plants. Additionally, the costs of producing bioelectricity and biohydrogen via electrolysis using vinasse biogas from Brazil's sugar/alcohol industry were determined, factoring in the payback period, equivalent utilization period, and annual interest rate. The study demonstrates the efficiency and cost-effectiveness of producing biohydrogen using vinasse biogas. The cost of producing bioelectricity at the two plants decreases significantly over the 25-year system implementation period, starting at around 0.09–0.08 USD/kWh in the first year and dropping to a minimum of 0.027–0.039 USD/kWh by the end of the period. The initial cost of producing biohydrogen ranges from 0.24 to 0.25 USD/kWh at São Jose da Estiva and from 0.30 to 0.32 USD/kWh at São Manoel in the first year. However, prices drop by nearly half in the second year, reaching 0.05 to 0.06 USD/kWh at São Jose da Estiva and 0.06 to 0.07 USD/kWh at São Manoel. The payback period for the biohydrogen and bioelectricity production system increases, with São Jose da Estiva generating income by 1st year for a 4% to 12% interest rate. For São Manoel, income is expected by the 1.5 year for a 4% to 12% interest rate. Both plants recover their investment within the first 2 years of operation. By the 10th year, São Jose da Estiva's income is projected to be between 3,888,501.96 USD (4%) and 3,678,407.29 USD (12%), while São Manoel's income is expected to range from 3,123,824.69 USD (4%) to 2,932,050.63 USD (12%), demonstrating that the system is viable for sugar and ethanol plants.

Keywords: biohydrogen; bioelectricity; vinasse biogas; electrolysis; energetic analysis; economic analysis



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1. Introduction

In recent years, it has been observed that the demand for more sustainable energy sources is on the rise, due to the reduction in oil and natural gas reserves. The pursuit of solutions aimed at mitigating or eliminating greenhouse gas emissions has prompted nations endowed with substantial resource generation infrastructure to explore alternative paths. As the world shifts to cleaner energy, hydrogen (H₂) emerges worldwide as a potential energy vector because it can be stored and used to produce electricity (fuel cells or power systems), heat (combustion), or both (cogeneration). Developing a hydrogen-based

economy could improve energy security, restructure the existing energy infrastructure, and revitalize the chemical and mining industries [1]. H_2 is also crucial for reducing carbon emissions, especially in industries, as it helps make better use of renewable energy sources [2]. For this reason, renewable H_2 provides an opportunity for zero-emission industry, power and heat generation, and transportation. Its benefits are already being recognized in specific business sectors.

This article focuses on the production of H_2 through electrolysis, powered by electricity produced from vinasse biogas. Therefore, it is necessary to study some important aspects to understand the system that will be implemented here. First, hydrogen and its different types are explained. Then, an analysis of Brazil's sugar-alcohol industry is presented, where the country's infrastructure for ethanol production, and consequently vinasse, is evaluated. Vinasse, a byproduct of ethanol distillation, undergoes anaerobic digestion in a reactor, producing biogas, which later powers a system consisting of an internal combustion engine and an electricity generator to initiate the electrolysis process.

1.1. Hydrogen

It is important to understand why it is important to conduct these types of studies to produce hydrogen (H_2). H_2 is increasingly being recognized as a crucial element in shaping the future energy landscape and promoting sustainable development for the planet. H_2 is also one of the bases of the energy transition since it can be used both as an energy carrier and as a feedstock. It is believed that by 2050, H_2 will provide 18% of end-user energy, eliminate six metric gigatons of carbon emissions, produce nearly USD 2.5 trillion in sales, and create almost 30 million jobs worldwide [3].

Hydrogen is classified into different color categories: blue, gray, brown, black, and green, based on its hydrogen production technology, energy source, and environmental impact.

1.1.1. Blue Hydrogen

This is produced from the steam reforming of natural gas. During this process, natural gases react with steam to produce H_2 and CO_2 . Of the CO_2 produced, between 85% and 95% is captured and stored underground using industrial carbon capture and storage (CCS) techniques, while the remainder of the generated CO_2 cannot be captured. Additionally, the long-term impacts of storage are uncertain, and leaks may still negatively affect the environment and climate [4,5].

1.1.2. Gray Hydrogen

This is produced from non-renewable fossil fuels, such as natural gas or coal, through the steam reforming/autothermal reforming process. This process is like the blue hydrogen process, but the CO_2 produced is not captured and is directly released into the atmosphere [4,5].

1.1.3. Brown Hydrogen

Currently, this is the most widely used type, produced from raw materials rich in hydrocarbons (lignite coal or methane) through the gasification process. However, as a result, each ton of brown hydrogen releases 10–12 tons of CO_2 into the atmosphere [1,4].

1.1.4. Black Hydrogen

This is produced from the gasification of coal. During the coal gasification process, syngas is produced in the gasifier, and hydrogen can be separated from the other gases using special absorbers or membranes, while the other gases can be released into the atmosphere [1,4].

1.1.5. Green Hydrogen

This is produced from renewable water and electricity through the electrolysis process. In this process, water is split into H_2 and O_2 under the influence of electricity with zero carbon emissions [5]. It is also understood that “green hydrogen” is generally conceived as H_2 produced by electrolysis. The general definition of green hydrogen relates to the absence of CO_2 emissions, that is, it is produced through technologies that use renewable sources or carbon-neutral technologies. Therefore, H_2 produced from biomass is considered CO_2 -neutral and can be defined as “green”.

As explained above, H_2 can be produced via several different processes, including steam methane reforming (SMR), coal gasification, biomass gasification, and water electrolysis. Currently, 96% of the H_2 produced is grey hydrogen, which comes from SMR of natural gas and coal gasification. It releases 830 Mt of CO_2 per year, which is not environmentally or climate-friendly [6]. Hence, both processes require the implementation of carbon capture and storage (CCS) to mitigate their carbon emissions. The application of CCS for coal gasification is a complex attempt, and the technology is still in the early stages of commercial deployment [1].

Alternative H_2 production technologies, such as biomass gasification and water electrolysis, are gaining prominence. However, the efficiency of H_2 production faces challenges, particularly in the presence of contaminants, such as tar from the biomass gasification, which should be eliminated [7]. In contrast, water electrolysis offers a route to high-purity H_2 production without carbon emissions, taking advantage of renewable energy sources for the generation of green hydrogen.

1.2. Electrolysis

Water electrolysis has been a well-known technology for green H_2 production for over two centuries. Electrolysis requires an electric current passing through an electrolytic conductor, such as alkaline, polymeric, or solid oxide materials. This process leads to the splitting of water molecules into hydrogen (H_2) and oxygen (O_2). An anode facilitates the oxidation reaction, resulting in the release of O_2 from water. A cathode facilitates the reduction reaction that captures H_2 from water. Consequently, this process yields H_2 with significant energy potential.

Currently, there are three main electrolysis technologies: alkaline water electrolysis (ALK), polymer electrolyte membrane (PEM) electrolysis, and solid oxide electrolyzer cells (SOECs).

1.2.1. Alkaline Water Electrolysis (ALK)

This is the most mature technology, used since 1920, with about 70% of the market share. It offers low costs and long operational life but requires continuous operation to prevent damage, making it less compatible with variable renewable energy sources. Additionally, it has low current densities and faces corrosive conditions [8].

1.2.2. Polymer Electrolyte Membrane (PEM)

In operation since 1960, PEM is more efficient and compact, making it suitable for urban areas and capable of quickly capturing excess renewable electricity. It can also produce high-pressure hydrogen without additional conversion steps, enhancing overall efficiency. However, it has higher capital costs due to expensive materials and catalysts. Potential supply issues could arise in a mature PEM market due to socio-economic factors [9].

1.2.3. Solid Oxide Electrolyzer Cells (SOECs)

The SOEC is a newer technology with about 150 kW installed capacity. It operates at high temperatures (700 to 1000 °C), which improves efficiency by using less electricity and allows heat integration. However, SOECs face challenges like instability, delamination of electrodes, and safety concerns [10].

Notably, the H_2 produced via this method exhibits high purity (>99.95%) compared to other methods, as it does not generate carbon, sulfur, or nitrogen compounds [4].

1.3. Brazilian Sugar and Ethanol Industry

Brazil, the world leader in sugarcane production, is the case of study in this paper. It has a total area of 850 million hectares, with nearly 1% used exclusively for sugarcane production, capable of producing up to 72 tons per hectare [11]. The sugarcane industry in Brazil extends beyond sugar production, with sugar sales constituting a mere 53% of overall profits. Derivatives such as ethanol, adopted as a fuel source since the 1930s, contribute significantly, representing 42% of profits. Additionally, the sale of electricity accounts for the remaining 2% [11]. Contemporarily, the sugarcane and alcohol industry in Brazil adopts a circular framework, optimizing various aspects of its operations. For example, sugar and alcohol plants already power their internal network with electricity from sugarcane bagasse burning. They use vinasse, a byproduct of ethanol rich in magnesium, phosphorus, and potassium, as fertilizer. And some others are creating second-generation ethanol from first-generation production waste.

Brazil also has the conditions to become one of the leaders in the production of green hydrogen, exploring different routes to obtain the gas. The country is standing out on the global renewable energy scene, with its potential to produce almost 2 billion tons of green hydrogen [12]. This resource has become a promising and sustainable alternative amid the energy transition scenario in the world, which is still heavily based on fossil fuels, which makes the search for renewable energy sources an urgent priority. In this context, Brazil stands out, not only for the extensive network of hydroelectric plants in operation but also for the significant growth in solar and wind energy in recent years. In Figure 1, a map of Brazil is shown with some of the current green hydrogen generation projects throughout the territory, and in Table 1 it is shown the translation of the text in the figure.

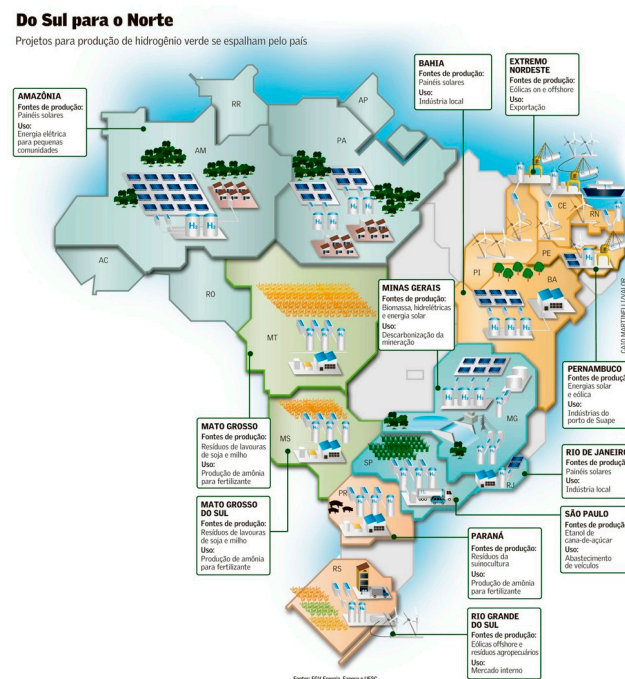


Figure 1. Projects for green hydrogen production in Brazil [12].

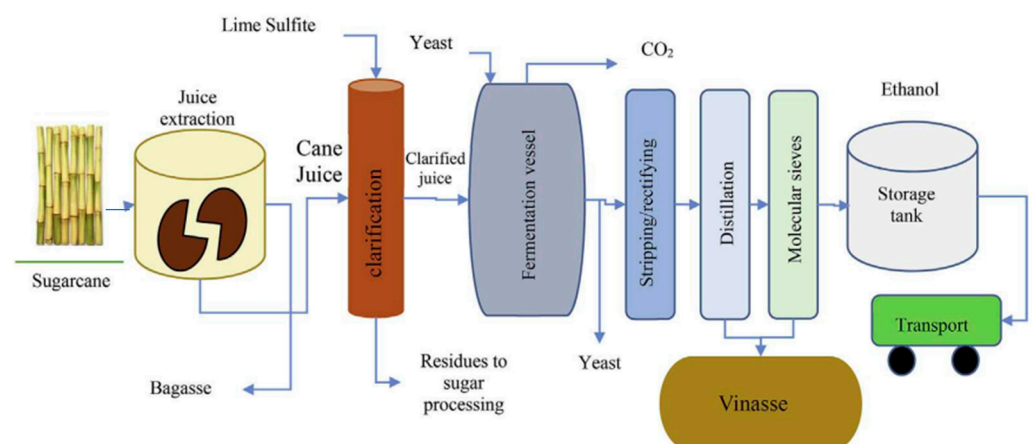
Table 1. Translation of Figure 1. Projects for green hydrogen production in Brazil.

Region/State	Production Sources	Use
Amazonia	Solar Panels	Electrical Energy for Small Communities
Bahia	Solar Panels	Local Industry
Rio de Janeiro	Solar Panels	Local Industry
Extremo Nordeste	On and Offshore wind farms	Exportation
Minas Gerais	Biomass, Hydroelectric and solar energy	Mining Decarbonization
Pernambuco	Solar and Wind Energy	Suape Port Industry
São Paulo	Sugarcane ethanol	Vehicle Supply
Rio Grande do Sul	Offshore wind farms and agricultural waste	Internal Market
Paraná	Pig farming waste	Ammonia Production for Fertilizer
Mato Grosso	Residues from soybean and corn crops	Ammonia Production for Fertilizer
Mato Grosso do Sul	Residues from soybean and corn crops	Ammonia Production for Fertilizer

As shown in Table 1, there are already several green H₂ production projects using renewable energy in Brazil. For instance, in the northern and northeastern regions, solar and wind energy are the most applied due to the geographical location of these regions in the tropics. Meanwhile, in the central and southern regions, technologies for green H₂ production are preferred, using waste from sugar, alcohol, corn, and soy production plants, among others. This demonstrates that the country is already encouraging the use of these technologies. Primarily, the multifaceted approach within Brazil's sugarcane and alcohol industry positions it as a formidable contender in the ongoing quest for innovative energy and H₂ acquisition methodologies.

1.4. Vinasse

With every industrial process comes highly harmful waste, which, if not properly disposed of, leads to harmful impacts on soil and water sources, and an increase in greenhouse gas emissions, thus polluting the environment. In the sugarcane-alcohol industry, we have vinasse, considered the major contaminant in ethanol production, as it is a severe and recalcitrant product [13,14]. It is a liquid produced in the rectification and distillation unit in the production of bioethanol; the production process is shown in Figure 2.

**Figure 2.** Sugarcane vinasse production process [15].

Its properties vary widely, depending on the composition of its elements, as well as the operating conditions used in the ethanol production plant. It is obtained in the distillation

process specifically at temperatures between 65 °C, in vacuum processes, and 107 °C, in atmospheric distillation processes, with a pH between 3 and 5, which also depends heavily on the conditions of sugarcane cultivation and harvest [14,16]. Now, most vinasse components are organic matter, around 75%, including non-fermentable substances like glucose and fructose, fermented products that could not be separated during distillation, such as glycerol and organic acids, and residual yeast that could not be separated during the industrial process.

Vinasse exhibits a high concentration of solids and a significant Chemical Oxygen Demand (COD). This 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 [16]. The total solids (TS) content in vinasse 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 [17]. In fact, vinasse can contain even higher levels, reaching up to 299,250 mg/L [16]. Due to these substantial amounts of solids, 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 [14].

However, vinasse has the highest potential for biogas production through anaerobic digestion, thus presenting economic and environmental benefits.

1.5. Anaerobic Digestion

There are some methods for treating these organic wastes, but anaerobic digestion (AD) has proven to be very useful on a large scale. This is a method where complex organic components are biologically converted through fermentation, in which the environment is oxygen-poor, into various compounds, including methane, carbon dioxide, ammonia, and water, among other chemicals.

The AD process consists of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. These stages are key to understanding how organic matter is biochemically digested into carbon dioxide and methane by anaerobic microorganisms.

1.5.1. Hydrolysis Process

In the first stage of AD, insoluble organic compounds like proteins, fats, and carbohydrates are broken down into soluble compounds such as amino acids and fatty acids, facilitated by hydrolytic enzymes [18,19].

1.5.2. Acidogenesis Process

During this second stage, microorganisms convert organic matter into alcohols or short-chain fatty acids. Acetic acid plays a central role in methane formation. pH levels above 5 increase volatile fatty acid production, while pH levels below 5 promote ethanol production [19,20]. Key reactions include glucose converting to ethanol, propionate, and acetic acid.

1.5.3. Acetogenesis Process

In this stage, acetogenic bacteria convert volatile fatty acids into acetate, hydrogen, and carbon dioxide. Hydrogen plays a crucial role, and low hydrogen pressure is essential for these reactions. Various substrates influence the final products, such as propionic and butyric acids [18].

1.5.4. Methanogenesis Process

The final stage involves methane formation through reactions between hydrogen and acetic acid. This slow process is sensitive to factors like temperature, pH, and organic loading rate [21]. Methane is produced through reactions like the reduction of carbon dioxide and the conversion of acetic acid [18,19].

1.6. UASB Reactor

AD occurs in digesters, which can operate in batches or continuous flow. For sugar and alcohol products, continuous flow is most suitable due to the large volume of vinasse that is generated by the plants, as is the case with the Up-flow Anaerobic Sludge Blanket Reactors (UASB Reactors) [19].

UASB reactors have the highest success rate for AD of fresh vinasse. Since it has low solid content, these reactors enable pumping and recycling, and thus a low hydraulic residence time, unlike what occurs in other digesters [22]. Several studies have explored biogas generation from the AD of vinasse. Ref. [23] examined the thermophilic anaerobic digestion of sugarcane vinasse in a two-stage UASB reactor, achieving a 58% increase in methane and energy production compared to a single-stage system. Ref. [13] evaluated a two-step anaerobic co-digestion process using food waste and vinasse, achieving methane yields of 72.7% and hydrogen yields of 76.54%. These processes also contribute to environmental benefits by producing biogas and bio-fertilizers, offering a sustainable energy solution [24].

1.7. Biogas Obtained by Vinasse

There are two key benefits of converting vinasse into biogas in Brazil, beyond energy production and greenhouse gas reduction, that stand out. First, sugarcane is harvested during the dry season, when hydroelectric power, Brazil's main energy source, is reduced. Biogas can help offset this seasonal drop in hydroelectric production. Second, biogas can be stored, unlike other renewable sources like solar and wind, which require costly batteries. This storage capability helps reduce power supply interruptions on the Brazilian grid [14].

For a successful AD process, a balance of key nutrients—carbon (C), nitrogen (N), phosphorus (P), and sulfur (S)—is essential. If a certain substrate has too high a C/N ratio, or in other words, has nitrogen deficiency, it can disrupt the microbial community, reducing enzyme production needed for carbon utilization and resulting in lower methane yields [25]. On the contrary, substrates with excessive N can inhibit the AD process via accumulation of toxic ammonia (NH_3) produced from protein degradation or by urea conversion. P and S are also considered essential nutrients for the AD process. P supports microbial growth and energy production (ATP and NADP), while S is crucial for amino acids [14,23]. However, high sulfur concentrations can lead to issues, as sulfate-reducing bacteria outcompete methanogens for hydrogen and acetate, producing hydrogen sulfide (H_2S), which is toxic to bacteria. High H_2S levels can also cause corrosion in biogas plant components like power units, biogas systems, and metal parts, increasing maintenance costs [25].

AD of vinasse can be used to stabilize organic matter and produce biogas. Sulfates and most of the organic matter are removed, while some volatile components and nutrients (P, N, and K) are separated. Using this method, the S content in vinasse can be reduced to less than 1%. This is important to consider because the sulfur content in vinasse is 4 to 10 times higher than the optimal concentration required for biogas production [17]. After the sulfur content is reduced, the remaining components and high organic matter content make biogas production from vinasse highly viable. Also, due to its lack of lignin, obtaining biogas is simpler and faster than from other materials.

Finally, as was discussed earlier, this paper emphasizes exploring the potential of producing green H_2 by electrolysis power with vinasse biogas electricity generated in a motor/generator set. The main objective of this study is to conduct a comprehensive technical and economic analysis of green H_2 production using bioelectricity from vinasse biogas and investigate the potential for bioelectricity generation by utilizing the biogas derived from vinasse in various regions of Brazil. Then, we choose two sugarcane and alcohol plants in a state of Brazil to study the viability of invest in the system; examine operational aspects of the electrolysis process with water, specifically focusing on its operation with bioelectricity; assess the energy efficiency of biohydrogen production, considering the overall conversion efficiency and losses throughout the process; and determine the cost associated with the

production of biohydrogen and bioelectricity, considering factors such as equipment, raw materials, energy consumption, and operational expenses.

2. Materials and Methods

The system proposed for this work involves the following:

A set involving an internal combustion engine operating with vinasse biogas and an electricity generator is used, in which the production of bioelectricity will be studied. The chosen model is the CG260-16 from Caterpillar (Irving, TX, USA) [26], shown in Figure 3.

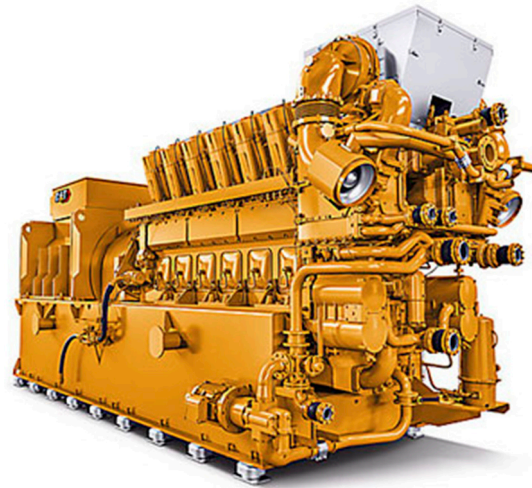


Figure 3. Caterpillar Model CG260-16 [26].

Next, this motor/generator set will be connected to an electrolyzer to assess the production of biohydrogen. The chosen model is the HySTAT 600 from Hydrogenics (Oevel, Belgium) [27], shown in Figure 4.

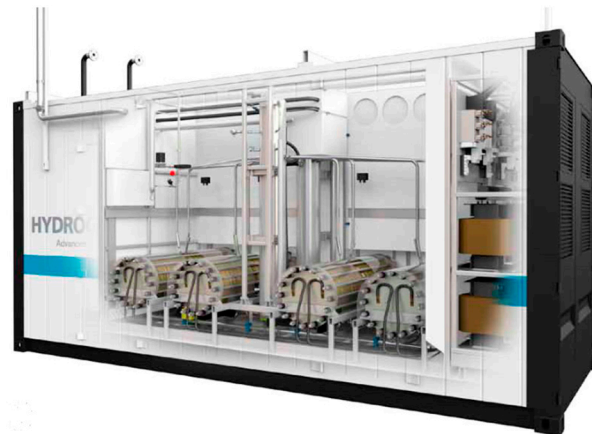


Figure 4. Hydrogenics HySTAT Model 600 [27].

As a case study, the potential for biogas generation in each region of Brazil will initially be analyzed, using data from the National Supply Company [28] for the harvests corresponding to the year 2022 until April 2023. After choosing a region, two ethanol plants in the selected region will be chosen to conduct an investment feasibility analysis of these plants in the proposed system. Following the selection of the plants, the potential for bioelectricity generation using the motor/generator set and the production of biohydrogen through electrolysis will be calculated, and an energy and economic analysis will then be conducted.

The analyses will examine several aspects, such as operational aspects of the water electrolysis process, focusing specifically on its operation with bioelectricity. They will

evaluate the energy efficiency of biohydrogen production, considering overall conversion efficiency and losses throughout the process. Additionally, the associated costs of biohydrogen and bioelectricity production will be determined, considering factors such as equipment, raw materials, energy consumption, and operational expenses.

2.1. Sugar-Alcohol Industry of Brazil

Brazil, being a vast country with diverse soil types, ecosystems, and climatic conditions, exhibits regional variations in the sugar and alcohol industry and its production. Each region has unique conditions that can either support or hinder the industry, resulting in differing levels of production.

In the national context, the sugar-alcohol sector recorded a production of approximately 610 million tons of sugarcane until April 2023 in the 2022/2023 season. Analyzing specific regions, the Southeast region stands out as the largest producer in the country, utilizing around 5127 thousand hectares and achieving a productivity of approximately 75.629 kg/ha. The Central West region, with approximately 1,767,000 hectares, reported a production of 131,592.2 thousand tons until April 2023. In the Northeast region, the estimated productivity is 64.313 kg/ha. The Southern region had an estimated area of 475,000 hectares with a productivity of 65.115 kg/ha. Lastly, the Northern region estimated that approximately 3823 thousand tons of sugarcane will be obtained in this region by the end of the current season [28]. The average annual production of ethanol for each region, during only the harvest of the 2022/2023 period until the month of April of 2023, is shown in Table 2.

Table 2. Average annual production of total ethanol by region (22/23 harvest) [28].

Region	Ethanol Production
North	263,151.0 m ³ /year
Northeast	2,048,658.9 m ³ /year
West Central	13,018,769.5 m ³ /year
Southeast	14,893,962.1 m ³ /year
South	1,113,168.0 m ³ /year
Total	31,337,709.5 m ³ /year

With this context, the West-Central and Southeast regions have been selected due to their significant difference in ethanol production compared to the other regions. These two regions stand out for their substantial contribution to the overall ethanol production in Brazil.

2.2. Vinasse Biogas Production Potential in the West-Central and Southeast Regions of Brazil

Vinasse biogas is generated through the anaerobic decomposition of organic residues present in vinasse. The quantity of vinasse produced can vary among ethanol producers; it is estimated that for each liter of ethanol produced, between 10 and 13 L of vinasse are generated [13,23,29]. And for this study, a main value of 12 m³ of vinasse per 1 m³ of ethanol was chosen based on the calculations provided by UNICA (União da Indústria de Cana-de-Açúcar) [26,30]. Under standard conditions of 0°C and 1 atm, it has been found that 1 g of COD can produce 0.35 L of methane gas. Therefore, at 35 °C and 1 atm, 1 g of COD can yield 0.395 L of methane gas. Consequently, 10 to 26.4 m³ of biogas, containing 60% methane, can be generated from 1 m³ of vinasse [15,31]. Taking the lower limit allow to observe the minimum energy that can be obtained from the given amount of biogas, the biogas flow rates of the two regions are shown in Table 3.

Table 3. Biogas flow rate of the West-Central and Southeast regions.

Region	Vinasse Production by Region (Taking 1 m ³ Ethanol—12 m ³ Vinasse)	Daily Production of Biogas by Region (1 m ³ Vinasse—10 m ³ Biogas)	Biogas Flow Rate by Region (m ³ /h)
West-Central	428,014.34 m ³ /day	4,280,143.40 m ³ /day	178,229.31 m ³ /h
Southeast	489,664.51 m ³ /day	4,896,645.07 m ³ /day	204,026.88 m ³ /h

2.3. Energy Power Supplied by the Fuel (Vinasse Biogas)

To calculate the energy power of the fuel in kilowatts (kW), it is necessary to use the lower calorific value of typical vinasse biogas, 23 MJ/m³, and its specific mass of 1.8428 kg/m³ [27,32]. The energy power supplied can be obtained using Equation (1) [33]:

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

To calculate m_{fuel} , multiply the biogas flow rate obtained in the previous part by the specific mass of the fuel, ρ_{biogas} , and then transform its units to [kg/s] as observed in Equation (2):

$$m_{fuel} = m_{biogas} \times \rho_{biogas} * \frac{1}{3600} \quad (2)$$

It is also necessary to adjust the units of the lower calorific value to [kJ/kg]. Finally, substituting these values in Equation (1), the energy potential of each region is obtained, as shown in Table 4.

Table 4. Mass flow of vinasse biogas and energy potential for each region selected.

Region	Mass Flow of Fuel Per Region	Energy Potential Generation
West-Central	91.23 kg/s	1,138,687.21 kW
Southeast	104.44 kg/s	1,303,505.15 kW

2.4. Selected Plants Form de Southeast Region

From Table 3, it was shown that the highest generation potential is the southeast region. This region corresponds to the states of Rio de Janeiro, São Paulo, Minas Gerais, and Espírito Santo. Since the state of São Paulo is the one with the greatest potential for generating biogas from vinasse, now it is necessary to analyze a sugar plant in that region and see its energy potential generation.

Two plants were selected from the state of São Paulo. The first one is Usina São Manoel, located in the interior of the state, in the municipality of the same name, which, in the 2021/2022 harvest, registered a production of 132,202.00 m³ of ethanol [34]. The second plant is the São Jose da Estiva plant, located in the municipality of Novo Horizonte, also in the interior of São Paulo, which, in the 2022/2023 harvest, registered an ethanol production of 155,700.00 m³ [35]. With each ethanol production value, it is possible to conduct the same calculations that were made previously, using the conversion factors explained in Section 2.2 (1 m³ de ethanol × 10 m³ biogas) it is possible to obtain the biogas flow rate for both plants, results are shown in Table 5.

Table 5. Biogas Flow rate for both plants.

Ethanol Plant	Average Production of Ethanol (year)	Biogas Flow Rate per Plant
São José da Estiva	155,700 m ³	2465.75 m ³ /h
São Manoel	132,202 m ³	1810.99 m ³ /h

Since this work goal is to intend to install a biohydrogen production system to see its feasibility, it would require the total load of the biogas flow rate obtained to see how much energy power can be obtained to supply not only the motor/generator set but also be able

to supply the energy power required from the electrolyzer. Also, it is important to have a strong source of fuel to be able to counter efficiency troubles, as it will be explained later, that working with Biogas involves some issues that makes it less efficient, like low energetic efficiency in the motor/generator set, or the presence of non-combustible substances in biogas, such as water and carbon dioxide, that can harm the combustion process [26,36]. Using Equations (1) and (2) it is obtained the energy power that can be supplied by the plants; these results are shown in Table 6.

Table 6. Energy power supplied by the fuel.

Ethanol Plant	Energy Power Supplied by the Fuel
São José da Estiva	13,626.71 kW
São Manoel	11,570.19 kW

2.5. Energetic Analysis

2.5.1. Energy Balance of the Motor/Generator Set for the Bioelectricity Generation Process

For the bioelectricity process, an internal combustion engine together with an electricity generator running on biogas is considered; the inputs and products of the process are presented in Figure 5.

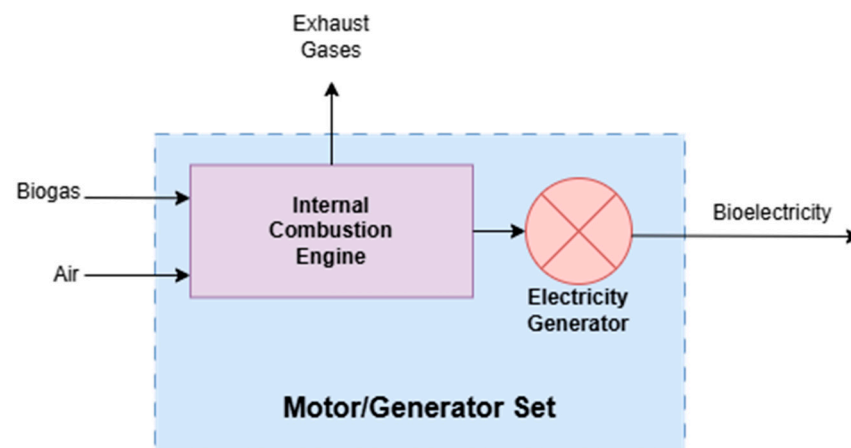


Figure 5. Flowchart of the bioelectricity process.

The selected motor/generator set for bioelectricity production in the electrolysis process is the CG260-16 model by Caterpillar. This model is versatile, capable of utilizing various fuel sources such as natural gas, biogas, coal gas, associated gas, and synthetic gas [37]. The key specifications and features of the CG260-16 model are provided in Table 7.

Table 7. Specifications and characteristics of the CG260-16 model [37].

Characteristics	Value
Electric Power (using Biogas)	3510 kW
Frequency	60 Hz
Electrical efficiency	43.2 %
Thermal efficiency	38.5 %
NO _x emissions	500 mg/Nm ³
RPM	900

It is seen that the electrical efficiency, η_{elICM} , of the model has a value of 43.2%. This manufacturer's electricity generation efficiency, which is found in the catalog, is significantly higher compared with reality. Some literature says that if this type of system is used for electricity generation using biogas, the electrical efficiency decays significantly [38];

indicates an electricity generation efficiency around of 25%, and [39] indicates a value of 28.45%, both considering ICM for biogas. So, for this work, an average value of 26.73% for the electricity efficiency, η_{elICM} , was used.

The power produced by the motor/generator set, E_{pICM} , can be calculated by Equation (3) [15,26,40]:

$$E_{pICM} = \eta_{elICM} \times E_{fuel} \quad (3)$$

The initial step involves the application of the fundamental principle, the first law of thermodynamics, which states the law of energy conservation to perform an energy balance, using Equation (4) [26,41]:

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

Since there is no cogeneration for the proposed case, Equation (4) can be rewritten as Equation (5), considering a single thermal power variable, E_{STP} , for engine cooling and exhaust gases [26]:

$$E_{fuel} + m_{air}h_{air} = E_{pICM} + E_{STP} + Losses \quad (5)$$

Regarding the losses, [26] recommends that they can be estimated at 8% of the total energy supplied by the fuel.

Through Equation (6), it is possible to determine the mass flow of biogas necessary to produce the electrical power in the motor/generator set, $m_{biogasICM}$ [27,40]:

$$m_{biogasICM} = \frac{E_{pICM}}{\eta_{elICM} \times LHV_{biogas}} \quad (6)$$

2.5.2. Energy Balance of the Electrolysis Process for Biohydrogen Production Process

For the biohydrogen process, the bioelectricity produced by the motor/generator set runs the electrolyzer, where the process of electrolysis will begin. The inputs and products of the process are presented in Figure 6.

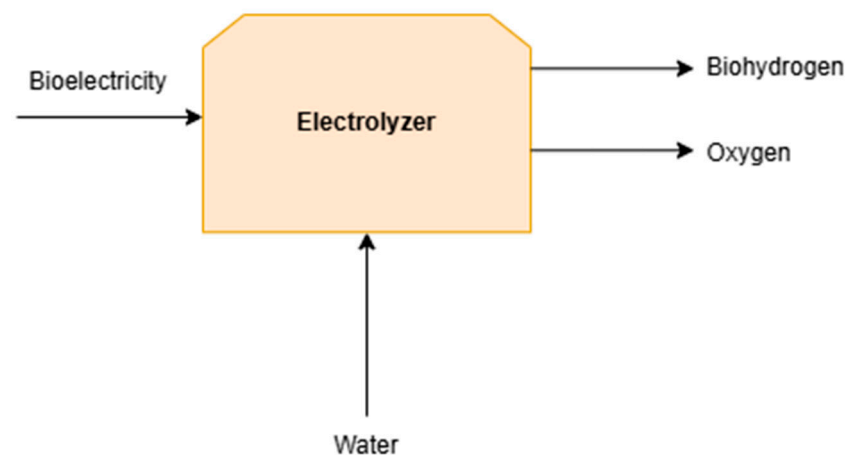


Figure 6. Flowchart of the electrolysis process for biohydrogen production.

For the selection of the electrolyzer, the electrical power required by it was considered, a value used as a parameter for the choice of the motor/generator sets available on the market. From Table 7, it is known that the model CG260-16 has 3510 kW of electric power and 43.2% efficiency. Table 8 shows the catalog of the company Hydrogenics, with the characteristics of the commercially available models of electrolyzer with production capacities from 4 to 1300 Nm³/h of biohydrogen [27,42].

Table 8. HySTAT™ Hydrogen Station Catalog [42].

	HySTAT® 10	HySTAT® 15	HySTAT® 30	HySTAT® 60	Long Scale
Capacity [Nm ³ /h]	4–10	6–15	12–30	24–60	120–1300
Operation Pressure [bar]	10 or 25	10	10	10	10
Expected Power Consumption [kWh/Nm ³]	5.0	5.0	5.0	4.9	4.9
Water Consumption [l/Nm ³ H ₂]			1.5–2.0		
Room Temperature			+5–40 °C		
Purity			99.9 % (99.999 % optional)		
Voltage and Frequency			Saturated H ₂ O, O ₂ < 1000 ppm 3 × 400/480/575 VAC, 50/60 Hz		
Options			Biohydrogen purification system, water treatment system, cooling system		
Dimensions		1.67 × 2.53 × 1.81 m		3.22 × 2.53 × 1.81 m	

Since the system will work with a load greater than 120 Nm³/h, only large-scale models meet the requirements. We selected the HySTAT 600 electrolyzer from the large-scale models, because the electrical power it needs to operate is similar to the electrical power generated by the motor/generator assembly. The electrolyzer specifications are shown in Table 9.

Table 9. HySTAT 600 specifications [27,42].

Characteristics	Value
Capacity	600 Nm ³ /h
Electric power	2940 kW
Water consumption	1.05 m ³ /h

The energy efficiency of the electrolyzer, $\eta_{electrolyzer}$, is determined with the data in Table 9 and Equation (7) [32,40]:

$$\eta_{electrolyzer} = \frac{m_{H_2} \times LHV_{H_2}}{E_{req_{elec}}} \quad (7)$$

The power supplied by the hydrogen produced, E_{H_2} , can be calculated with Equation (8) [32,40]:

$$E_{H_2} = m_{H_2} \times LHV_{H_2} \quad (8)$$

where the lower calorific value of biohydrogen is 120,000 kJ/kg. To find out the mass flow of hydrogen, based on the energy administered by both plants, the mass flow of hydrogen produced, m_{H_2} , is cleared from Equation (6), obtaining Equation (9):

$$m_{H_2} = \frac{\eta_{electrolyzer} \times E_{req_{elec}}}{LHV_{H_2}} \quad (9)$$

The analysis for this part is like the one described in the previous part, where it is used Equation (5). Modifying the variables, we obtain Equation (10):

$$E_{pICM} + m_{air}h_{air} = E_{H_2} + E_{STP} + Losses \quad (10)$$

Using Equation (10), it is possible to find the missing values of the energy balance of the electrolysis process, considering the same losses of 8% of the initial power delivered from the motor/generator set [26].

2.5.3. Energetic Analysis of the Complete System (Bioelectricity and Biohydrogen Production Process)

As previously explained, the electrolysis process requires an electrolyzer, which is fed with the bioelectricity obtained from the motor/generator set to obtain hydrogen from a solution with water. This complete process is represented in Figure 7.

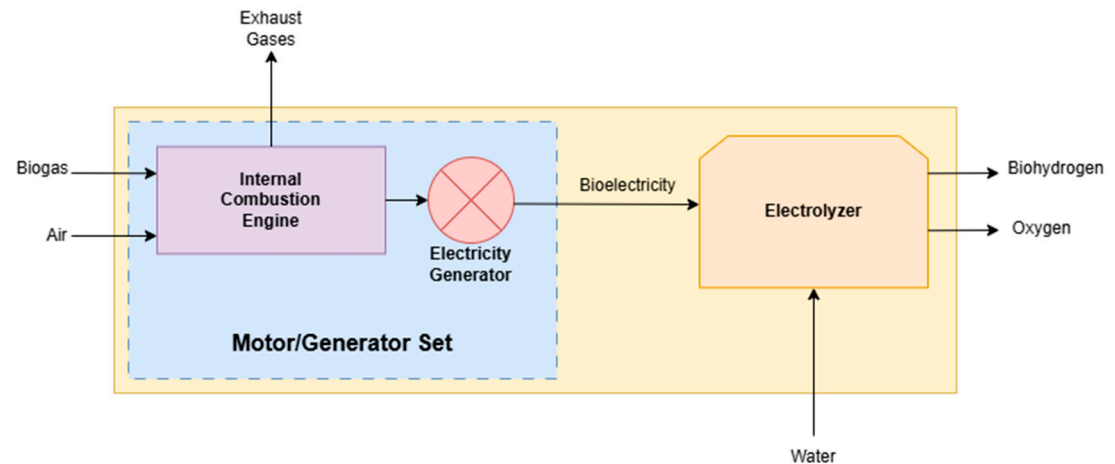


Figure 7. Flowchart of the biohydrogen production process using the bioelectricity made by the motor/generator set.

The electrical efficiency of the entire process, $\eta_{elec.elICM}$, with the electrolyzer connected by the motor/generator set burning vinasse biogas, is calculated using Equation (11) [27,32]:

$$\eta_{elec.elICM} = \eta_{electrolyzer} \times \eta_{elICM} \quad (11)$$

2.6. Economic Analysis

2.6.1. Economic Analysis of the Bioelectricity Generation Process

The economic analysis was conducted considering the energy power produced by the motor/generator set calculated in the previous part. It is developed from the calculation of the cost of producing bioelectricity, as well as the expected annual income, to determine the cost savings in energy throughout the years. The expenses with investment, operation, and maintenance of the generating plant and the cost of the fuel used (biogas) are considered [41]. The cost of the electricity produced by the motor/generator set, C_{elICM} , can be calculated using Equation (12):

$$C_{elICM} = \frac{I_{pICM} \times f}{H \times E_{pICM}} + C_{fuel} \times \frac{E_{fuel}}{E_{pICM}} + C_{manICM} \quad (12)$$

First, it is necessary to conduct some calculations first. The annuity factor, f , is calculated using Equation (13) [26,27,40]:

$$f = \frac{q^k \times (q - 1)}{q^k - 1} \quad (13)$$

where $q = 1 + \frac{i}{100}$, and i is the annual interest rate. The values selected are shown in Table 10.

Then, the investment cost of the motor/generator set, I_{pICM} , was calculated using the methodology proposed by Boehm [43], represented in Equation (14):

$$C = C_R \times \left(\frac{S}{S_R} \right)^m \quad (14)$$

Table 10. Annual interest rate and payback period.

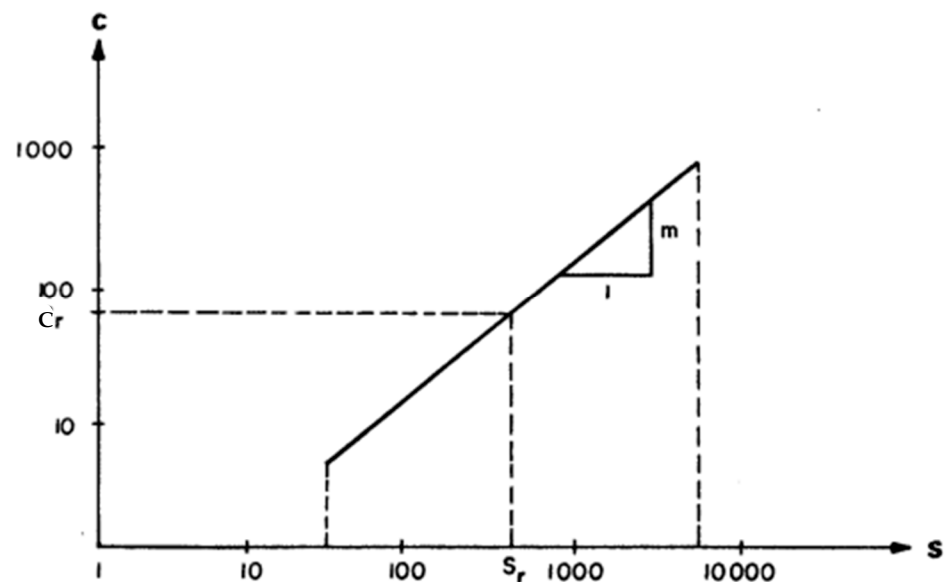
k	25 Years
i	4%
	8%
	12%

This is a technique used for estimating investment costs in thermal systems, where C is the cost of the equipment for a given quantity of interest S , and m is the incidence factor that indicates the estimated cost—its value is found between 0.5 and 1.0—and C_R is the cost of the equipment for a reference quantity S_R [43]. To apply the technique, the following steps are required:

Characterization of the equipment, which refers to finding the limits of the ranges for C and S , being $(C_{\max}, C_{\min})$ and $(S_{\max}, S_{\min})$. C_R is the average value between the cost range found in the characterization $(C_{\max}, C_{\min})$, and S_R is the average value between $(S_{\min}$ and $S_{\max})$ [43,44].

The incidence factor m is found from the tangent of the angle formed between a difference of one unit in S [43,44].

An illustration for this technique is shown in Figure 8.

**Figure 8.** Technique for estimating the investment costs in thermal systems [44].

With this methodology, it is possible to estimate the investment cost for the implementation of the motor/generator set, I_{pICM} . From Table 11 and Figure 9, it is possible to obtain Equation (15), for a power range between 500 and 4000 kW [27].

$$I_{ICM} = 1,508,334 \times \left(\frac{E_{pICM}}{3200} \right)^{0.25} \quad (15)$$

Table 11. Annual interest rate and payback period.

Capacity	Cost
2800 kW	USD 1,406,667.00
3600 kW	USD 1,610,000.00

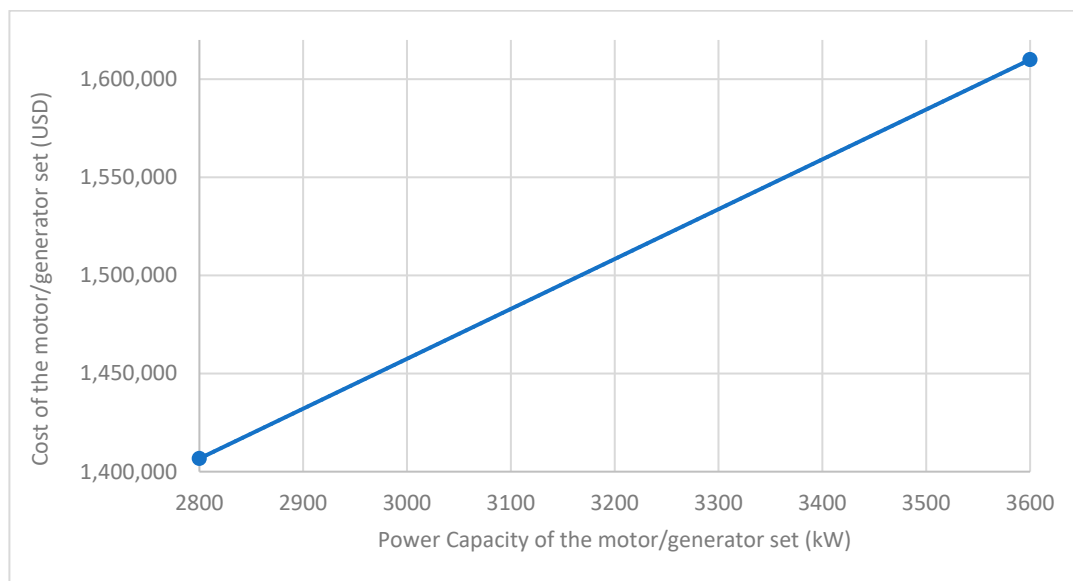


Figure 9. Methodology for determining the investment cost for the motor/generator set.

The work period H of the motor/generator set will be about 7300 h a year, equivalent to working 20 h a day, and the maintenance cost $C_{man_{ICM}}$ of the motor/generator set is 3% of the investment cost for the motor/generator set, according to Equation (16) [32,40]:

$$C_{man_{ICM}} = 0.03 \times \frac{I_{ICM} * f}{H * E_{p_{ICM}}} \quad (16)$$

Finally, it is necessary to calculate $C_{fuel} \frac{E_{fuel}}{E_{p_{ICM}}}$, from Equation (12). The production cost of biogas, C_{fuel} , varies widely in the market, considering the different sources it comes from, or the process used for its production. For this, a previous analysis was carried out, varying the fuel cost of biogas, C_{fuel} , in Equation (12) with values ranging from 0.005 USD/kWh to 0.025 USD/kWh [45], to visualize how the cost of electricity production would behave with variable fuel values. Figure 10 shows the results of this calculus.

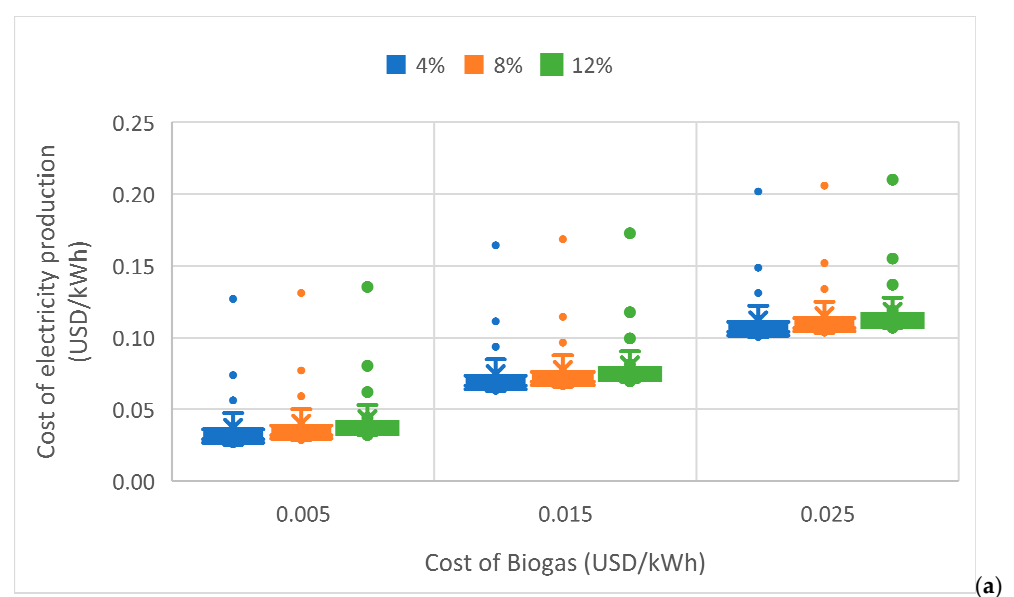


Figure 10. Cont.

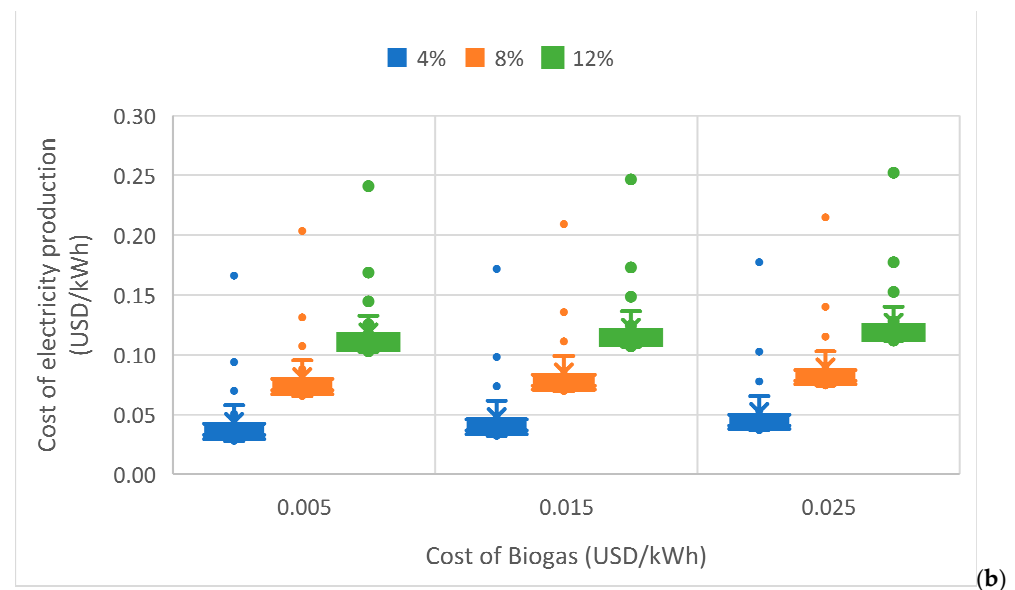


Figure 10. Cost of electricity production based on the cost of biogas for both ethanol plants. (a) São José da Estiva. (b) São Manoel.

The cost of electricity for industrial processes, C_{ele} , in the state of São Paulo is 0.145 USD/kWh [27]. It is seen that, for the worst-case scenario for both plants, where the annual interest rate is 12% and the cost of the fuel, C_{fuel} , is 0.025 USD/kWh, the cost of producing bioelectricity with the motor/generator set, C_{elICM} , for the São Jose da Estiva plant, reaches a maximum price of 0.21 USD/kWh, and for the São Manoel plant, its maximum price is 0.25 USD/kWh, just 0.05 USD more than the commercial cost. These prices are only for the bioelectricity production of the proposed system.

Every sugar and alcohol plant produces its own electricity through the combustion of bagasse; in this case, the electricity of cogeneration is not considered, to see if the system can self-sustain H_2 production only with the vinasse biogas as fuel. To continue the calculation of bioelectricity production, a fixed value was selected for C_{fuel} . For this case, the cost of vinasse biogas is needed, that is, 0.019 USD/kWh [18].

Finally, it is only necessary to conduct the calculation of the expected production of bioelectricity in the ethanol plants to continue later with the expected annual income of the investment of the system. Table 12 shows the fixed parameters that will be used in the economic analysis.

Table 12. Fixed parameters for the calculation for the investment cost of the motor/generator set.

Cost of fuel (vinasse niogas)	0.019 USD/kWh
Cost of electricity for industrial processes	0.145 USD/kWh
Sale price of biohydrogen	0.291 USD/kWh
Working period (hours per year)	7300 h

Now, we calculate the expected annual income from the production of bioelectricity from the motor/generator set, powered by the vinasse production plants, with Equation (17) [40]:

$$R_{ICM} = E_{pICM} \times H \times (C_{ele} - C_{elICM}) \quad (17)$$

2.6.2. Economic Analysis of the Biohydrogen Generation Process (Electrolysis Process Fed with Bioelectricity)

The analysis is the same as for the bioelectricity production process, only now the objective is to determine the cost of producing biohydrogen from the electrolysis of water, so some calculations vary. This cost can be calculated with Equation (18):

$$C_{H_2\text{electrolyzer}} = \frac{I_{\text{electrolyzer}} \times f}{H \times E_{H_2}} + C_{op\text{electrolyzer}} + C_{man\text{electrolyzer}} \quad (18)$$

Equation (19) allows calculating the operating cost of the electrolyzer:

$$C_{op\text{electrolyzer}} = \frac{E_{req\text{elec}} \times C_{el\text{ICM}}}{E_{H_2}} + \frac{m_{H_2O} \times C_{H_2O}}{E_{H_2}} \quad (19)$$

where the power required by the electrolyzer, $E_{req\text{elec}}$, is 2940 kW, the water cost, C_{H_2O} , for industrial processes in the state of São Paulo, for those who consume more than 50 m³/month, is 12.18 BRL/m³ [27] (0.21 USD = 1 BRL, updated on 16 November 2023). The mass flow of water from the electrolyzer, m_{H_2O} , is 1.05 m³/h [42]; the values with the corrected dimensions are shown in Table 13. The cost of electricity generated by the motor/generator set, $C_{el\text{ICM}}$, was obtained in the previous part.

Table 13. Parameters used for the operation cost of the electrolyzer with corrected dimensions.

	São José da Estiva	São Manoel
Power supplied by biohydrogen	2200.99 kW	1868.82 kW
Power required by the electrolyzer	2940 kW	
Water rate for industrial process	0.00256 USD/kg	
Mass flow of water in the electrolyzer	0.8329 kg/h	

The cost of electrolyzer, $C_{\text{electrolyzer}}$, for the biohydrogen production range from 0.1 kg/h to 100 kg/h can be estimated with Equation (20) [32]:

$$C_{\text{electrolyzer}} = 224.49 \times (m_{H_2})^{0.6156} * 10^3 \quad (20)$$

Equation (20) allows for a reliable estimation of the investment cost of electrolyzer equipment, $I_{\text{electrolyzer}}$. We consider production capacities of 100 Nm³/h and 1000 Nm³/h, which correspond to biohydrogen production rates of 8.99 kg/h and 89.9 kg/h, respectively. These values are in the range needed to use Equation (20); the results are shown in Table 14.

Table 14. Estimated cost of the electrolyzer using Equation (20).

Electrolyzer Capacity	Biohydrogen Flow Rate	Estimated Cost of the Electrolyzer
100 Nm ³ /h	8.99 kg/h	USD 867,623.82
1000 Nm ³ /h	89.9 kg/h	USD 3,580,399.32

For the next part, the Boehm Technique [43,44], used in the previous part, is also applied here; the values from Table 14 were drawn in Figure 11. This method helps the characterization of the equipment and permits the identification of parameters such as Cr , Sr , and m for Equation (14), while also accounting for typical equipment errors.

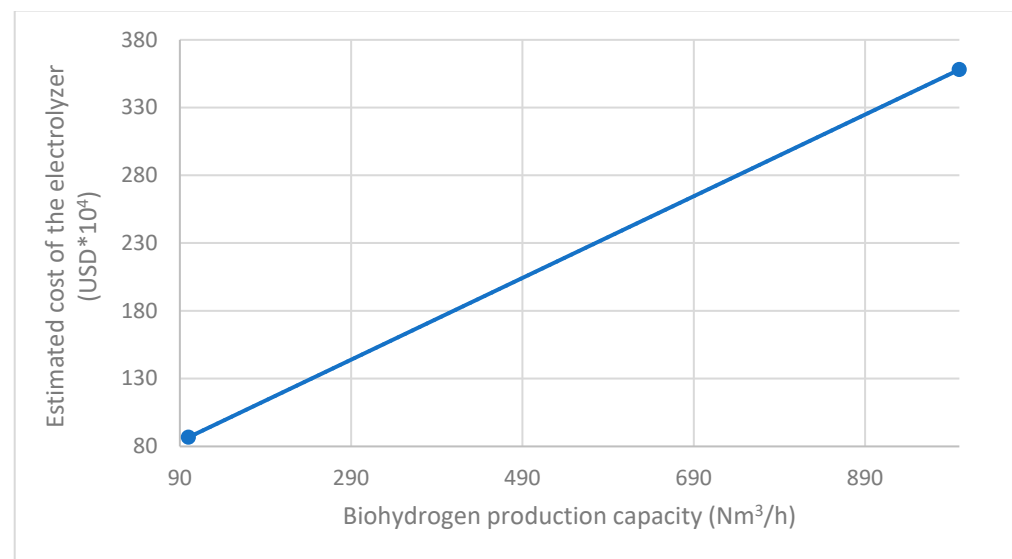


Figure 11. Methodology for determining the investment cost for the electrolyzer.

From Figure 11 and Equation (14) is possible to obtain Equation (21), to determine the investment cost of the electrolyzer, $I_{electrolyzer}$.

$$I_{electrolyzer} = 150 \times \left(\frac{P_{H_2}}{400} \right)^{0.71} * 10^4 \quad (21)$$

The maintenance cost of the electrolysis process, $C_{man_{electrolyzer}}$, is the same as Equation (16), where it can be considered as 3% of the investment cost of the plant; it is obtained with Equation (22) [26,27,40]:

$$C_{man_{electrolyzer}} = 0.03 \times \frac{I_{electrolyzer} \times f}{H \times \dot{E}_{H_2}} \quad (22)$$

To determine the projected annual income of the biohydrogen production system, R_{H_2} , which involves the use of the electrolyzer powered by bioelectricity supplied by the motor/generator set fueled by biogas from the São José da Estiva plant, a modified version of Equation (17) is employed, Equation (23). This modified equation incorporates some parameters considering the numerous factors involved in the biohydrogen production system, such as the electricity consumed by the electrolyzer, the specific work done by the electrolyzer, and the market price at which biohydrogen is sold. By applying this equation, a reliable estimate of the annual income generated by the system can be obtained.

$$R_{H_2} = E_{H_2} \times H \times (C_{H_2} - C_{H_2_{electrolyzer}}) \quad (23)$$

According to the International Energy Agency, 1 kg of green hydrogen, which can supply about 33.3 kWh, costs between EUR 8 and 10, which is between 0.238 EUR/kWh and 0.297 EUR/kWh [46] which, at the current (16 November 2023) exchange rate, the relationship is about USD 1 equal to EUR 0.92. So, for this case study, a mean value was selected between these values.

3. Results

3.1. Results of the Energetic Analysis

3.1.1. Results of the Energy Balance of the Motor/Generator Set for Bioelectricity Generation Process

The bioelectricity that can be produced by implementing the system in the selected plants for the study using Equation (3) is shown in Table 15.

Table 15. Bioelectricity produced by the motor/generator set using the fuel supplied by the plant.

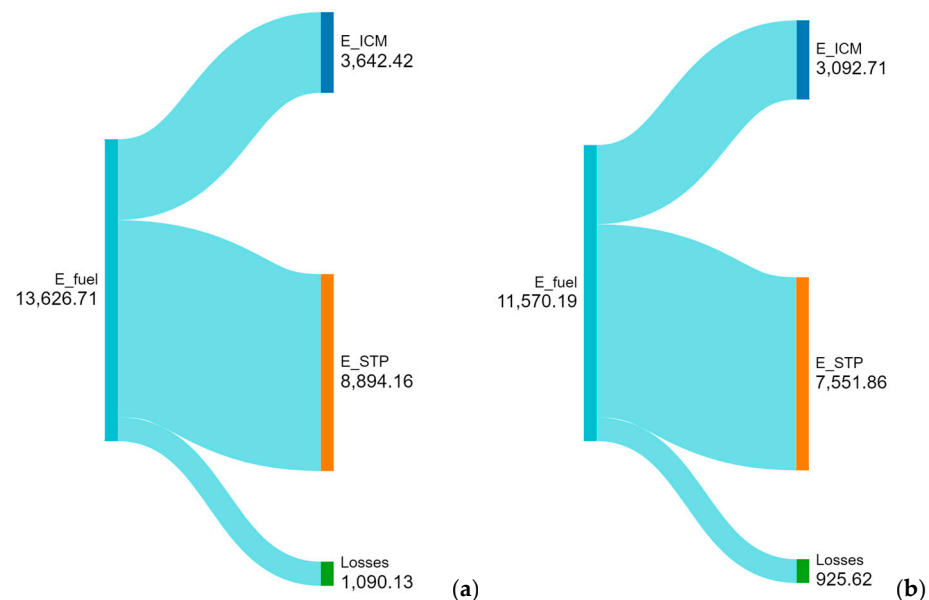
Ethanol Plants	Bioelectricity Produced
São José da Estiva	3642.42 kW
São Manoel	3092.71 kW

Therefore, the energy balance for the motor/generator set using Equation (5) would be as follows in Table 16.

Table 16. Energy balance of the electricity production process.

São Jose da Estiva	
E_{fuel}	13,626.71 kW
E_{pICM}	3642.42 kW
E_{STP}	8894.16 kW
Losses	1090.14 kW
São Manoel	
E_{fuel}	11,570.19 kW
E_{pICM}	3092.71 kW
E_{STP}	7551.86 kW
Losses	925.62 kW

Figure 12 presents the outcomes illustrated in a SANKEY diagram, which visually represents the distribution of the electrical power supplied by the fuel, vinasse biogas from the two plants: São Jose da Estiva first and São Manoel later. The figure shows the electrical power used by the motor/generator set, such as thermal power and the system losses.

**Figure 12.** SANKEY diagram of the energy balance of the motor/generator set. (a) São José da Estiva. (b) São Manoel.

The Lower Heat Value of biogas, LHV_{biogas} , with 55% CH_4 and 45% CO_2 , is 15,429 kJ/kg, and the molar mass is 52.08 kmol/kg [32]; these values are needed in Equation (6). Therefore, the result of the biogas flow is shown in Table 17.

Table 17. Mass flow of biogas in the motor/generator set.

Ethanol Plants	Mass Flow of Biogas	Mass Flow of Biogas
São José da Estiva	1386.42 Nm ³ /h	0.88 kg/s
São Manoel	1177.19 Nm ³ /h	0.75 kg/s

To transform the values from kg/s to Nm³/h, it is only necessary to know that the “N” means it is at 0 °C and 100 Kpa, and with the general law of gases, “ $PV = nRT$ ”, it is possible to transform mass values to volume values.

3.1.2. Results of the Energy Balance of the Electrolysis Process for Biohydrogen Production

The energy efficiency of the electrolyzer, together with the parameters used with its dimensions corrected, are shown in Table 18.

Table 18. Electrical efficiency of the electrolyzer.

Power Required in the Electrolyzer	2940 kW
Lower Heat Value of H ₂	120,000 kJ/kg
Mass flow of water in the electrolyzer	0.01479 kg/s
Energy efficiency of the electrolyzer	60.42%

Therefore, the energy balance results for the electrolysis process using Equation (10) would be as follows in Table 19.

Table 19. Energy balance of the biohydrogen production process.

São Jose da Estiva	
E_{pICM}	3642.42 kW
E_{H_2}	2200.99 kW
E_{STP}	1150.03 kW
Losses	291.39 kW
São Manoel	
E_{pICM}	3092.71 kW
E_{H_2}	1868.82 kW
E_{STP}	976.47 kW
Losses	247.42 kW

Figure 13 presents the outcomes illustrated in a SANKEY diagram, which visually represents the distribution of electrical power supplied by biohydrogen, from each of the two plants, in the same way as in Figure 12, showing the electrical power used by the electrolyzer, such as thermal power and the system losses.

The mass flow of hydrogen produced, m_{H_2} , and the power supplied by the hydrogen, E_{H_2} , for both plants are shown in Table 20.

Table 20. Mass flow of biohydrogen and energy power supplied by the biohydrogen production of both plants.

Ethanol Plants	Mass Flow of Biohydrogen	Power Supplied by Biohydrogen
São José da Estiva	0.0183 kg/s	2200.99 kW
São Manoel	0.0156 kg/s	1868.82 kW

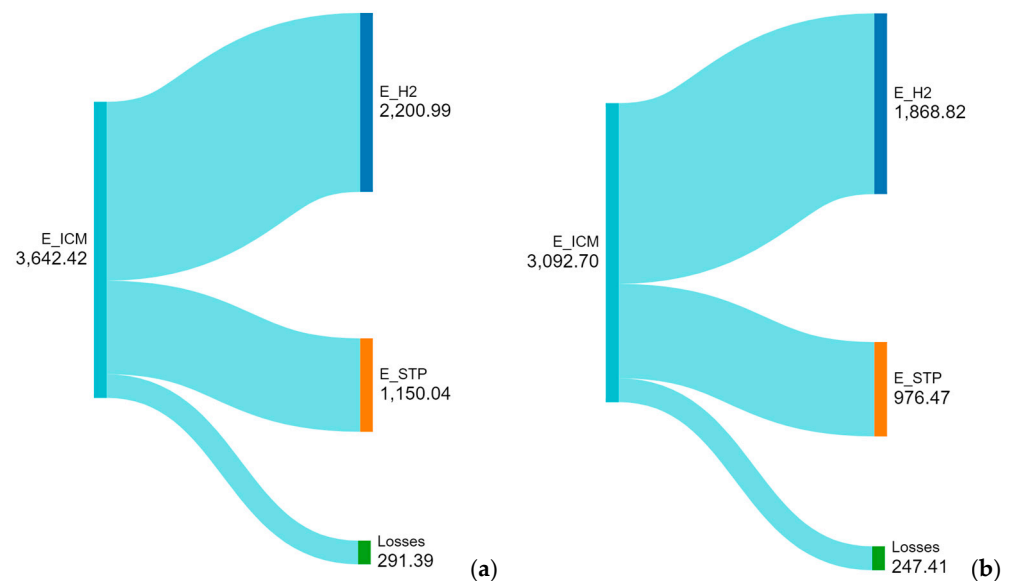


Figure 13. SANKEY diagram of the energy balance of the electrolysis process for biohydrogen production. (a) São José da Estiva. (b) São Manoel.

3.1.3. Energy Efficiency of the Complete System (Bioelectricity Generation with Biohydrogen Production)

From the characteristics of the CG260-16 model, it was known that the electrical efficiency of the motor/generator set $\eta_{electrolyzer}$ is 43.2% [37]. It was explained before why this value was not accurate for this article, so the value of 26.73%, was chosen [26]. For the next part, it is necessary to have the low heat value of hydrogen LHV_{H_2} , which is 120 MJ/kg, and, adjusting the dimensions of the hydrogen production capacity, which remains at 0.015 kg/s, using Equation (7), it is obtained that the electrolyzer efficiency is 60.385%. These values are replaced in Equation (11), obtaining the electrical efficiency of the entire process, $\eta_{elec.elICM}$, using the power produced in the motor/generator; values are shown in Table 21.

Table 21. Energy efficiency of the complete process (bioelectricity generation and biohydrogen production).

Electric efficiency CG260-16 model	26.73%
Electric efficiency HySTAT 600	60.39%
Global efficiency of the system	16.14%

Figure 14 shows the SANKEY diagram of the complete process, including the production of bioelectricity made by the motor/generator set using vinasse biogas and then the production of biohydrogen made by the electrolysis process in the electrolyzer.

3.2. Results of the Economic Analysis

3.2.1. Economic Analysis of the Bioelectricity Generation Process

E_{pICM} is replaced in Equation (15) by 3510 kW, the value corresponding to the power capacity of the motor/generator set, the Caterpillar CG260-16, making it possible to obtain the value in dollars of investment in the equipment, shown in Table 22.

Table 22. Investment value for the motor/generator set.

Motor/Generator Set	Investment
Caterpillar CG260-16	USD 1,543,449.66

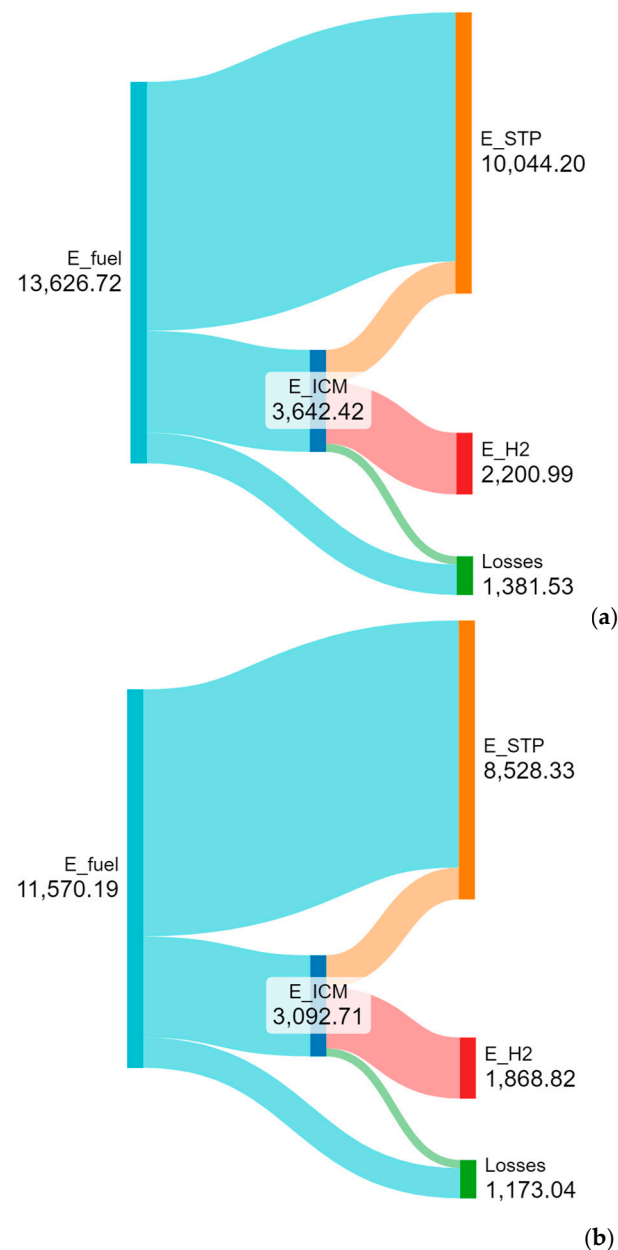


Figure 14. SANKEY diagram of the energy balance of the entire process. (a) São José da Estiva. (b) São Manoel.

All the calculations were made using Equation (12), Tables 10 and 12, to be able to obtain the cost of the bioelectricity produced by the motor/generator set, fed by the two plants separately, shown in Figure 15.

Considering that the actual cost of electricity for industrial process, C_{ele} , for the state of São Paulo is around the 0.14 USD/kWh, it can be seen that the cost of producing bioelectricity, C_{eICM} , using biogas from the 100% of their vinasse production with the implementation of the motor/generator set, for both plants will be low before the very first year of implementation of the system, having prices below 0.09 USD/kWh for São José da Estiva and 0.10 USD/kWh for São Manoel.

The results of the annual income for the implementation of the motor/generator set are shown in Figure 16.

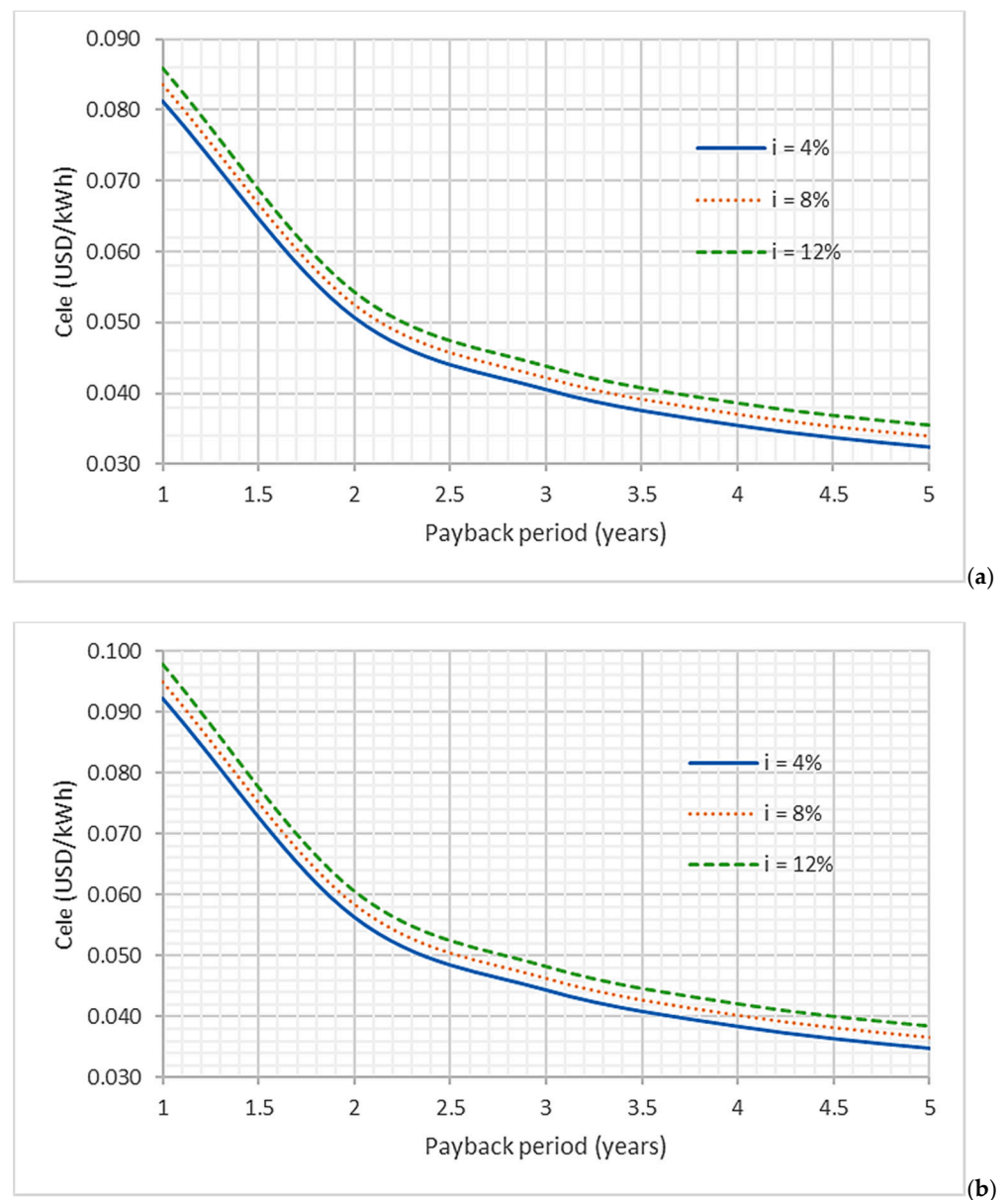


Figure 15. Cost of bioelectricity produced by the plant in a term of 25 years. (a) São José da Estiva. (b) São Manoel.

Here it can be seen that for both plants, the time of return on the investment in the motor/generator set will be less than two years: for the São José da Estiva plant and for the São Manoel plant, the return will come before the first year of the system implementation and they will have an expected income of 1,695,245.00 USD for a 4% of interest and 1,568,065.00 USD for a 12% of interest for São José da Estiva, and 1,189,881.00 USD (4%) and 1,062,701.00 USD (12%) for São Manoel. This income is only gained if they were sell 100% of the bioelectricity, but in this work, the 100% of the bioelectricity produced will run the electrolyzer to produce biohydrogen, so the real income will be studied in the next part where the biohydrogen produced by the bioelectricity is sold. Now, in terms of feasibility, this means that the investment in this type of system to generate bioelectricity is viable for common sugar and ethanol plants with a mean production of 150,000 m³/year.

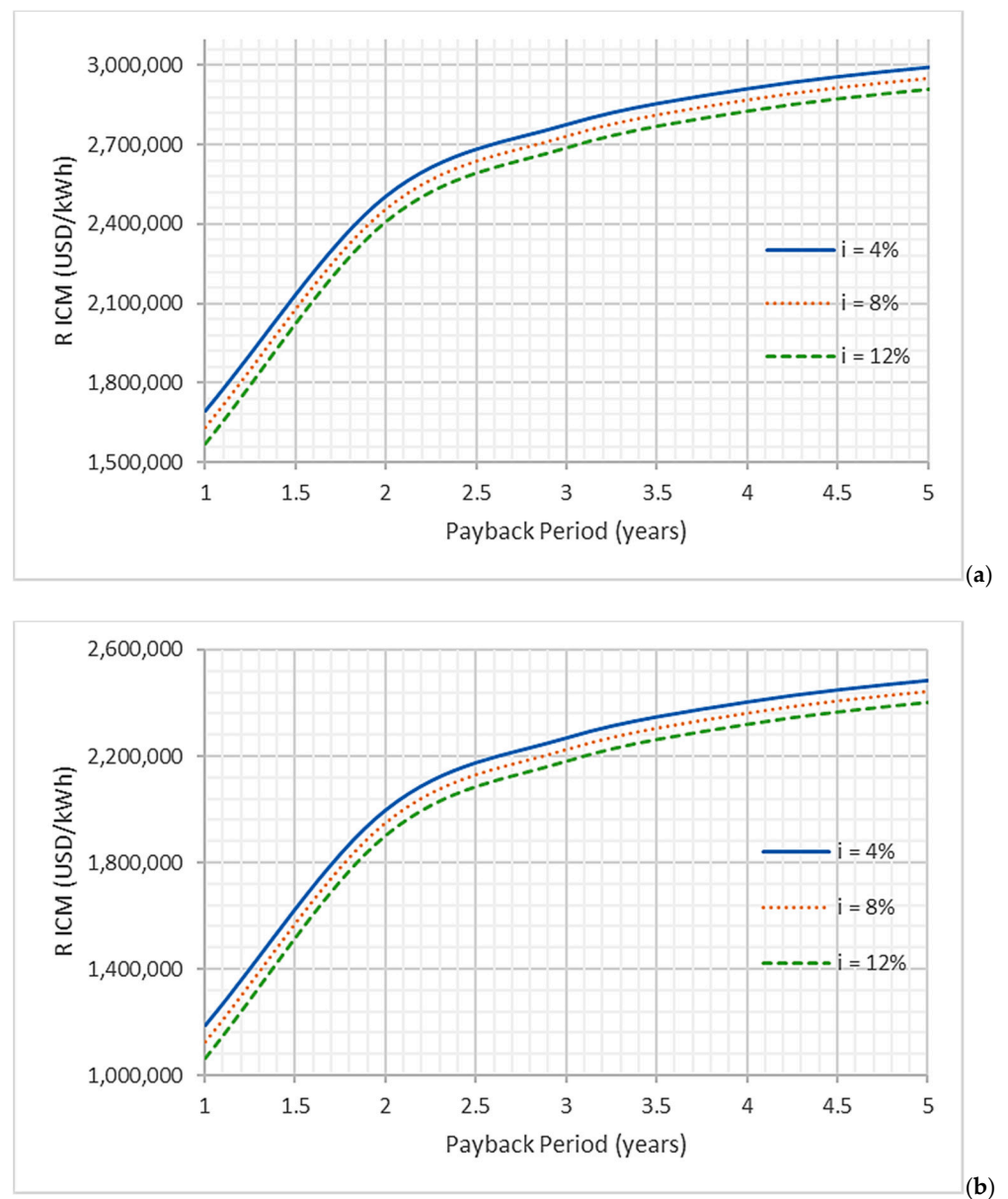


Figure 16. Expected annual income from the bioelectricity production of the motor/generator set using the energy supplied by the plants. (a) São José da Estiva. (b) São Manoel.

3.2.2. Economic Analysis of the Biohydrogen Production Process

The model chosen was the HySTAT 600 from Hydrogenics, with a production of $600 \text{ Nm}^3/\text{h}$ of biohydrogen. If this value is replaced in Equation (21), the investment cost from the electrolyzer is shown in Table 23.

Table 23. Investment cost for the electrolyzer HySTAT 600.

Electrolyzer Capacity	Biohydrogen Flow Rate	Estimated Cost of the Electrolyzer
$600 \text{ Nm}^3/\text{h}$	53.26 kg/h	USD 2,000,396.35

The cost of biohydrogen production based on a period of 25 years of the implementation of the system is shown in Figure 17.

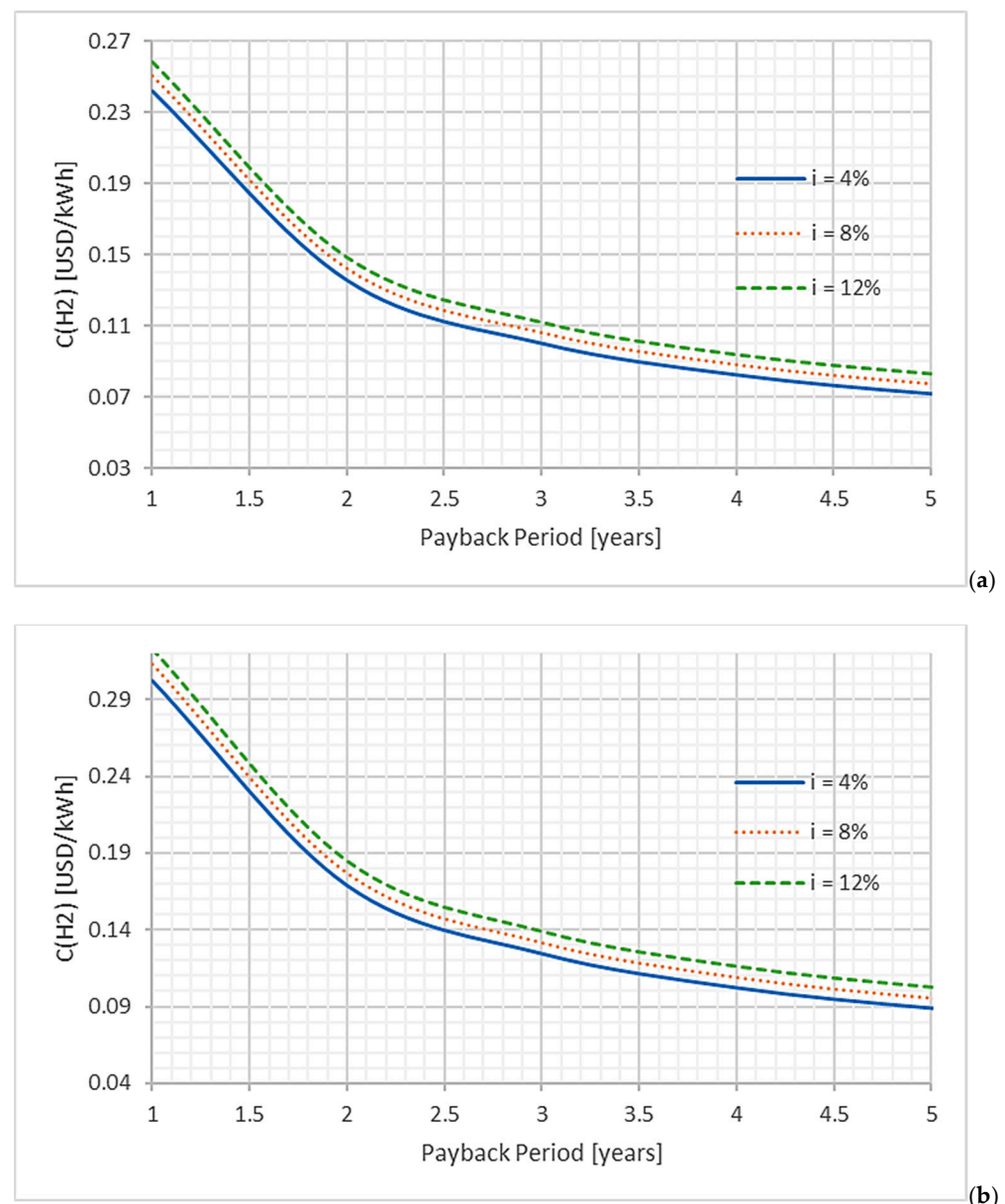


Figure 17. Cost of biohydrogen production from the electrolyzer. (a) São José da Estiva. (b) São Manoel.

Now, considering the complete process of biohydrogen generation using the bioelectricity produced by the motor/generator set to run the electrolyzer, and knowing that the hydrogen production price in the market is 0.29 USD/kWh [46], it can be observed that in the first five years of implementation, the production prices decay significantly below the market price. The market price is reached before the first year for São José da Estiva, and before 1.5 years for São Manoel. Therefore, it is inferred that within the first 10 years of system use, an annual income from the system is expected. This is shown in the following graphs.

The values required for the calculation of the annual income for biohydrogen production, using Equation (23), Tables 10 and 12, give the results shown in Figure 18.

In the case of the São José da Estiva plant, the return period for the investment in the system is before its first year of use for the cases of 4% and 8% of interest, and for its worst scenario, 12% of interest, the return is expected in the first year. In the second plant, São Manoel, the return of the investment time is a little longer, having the return after the first year for all the interest cases, but in all three before reaching the second year of use.

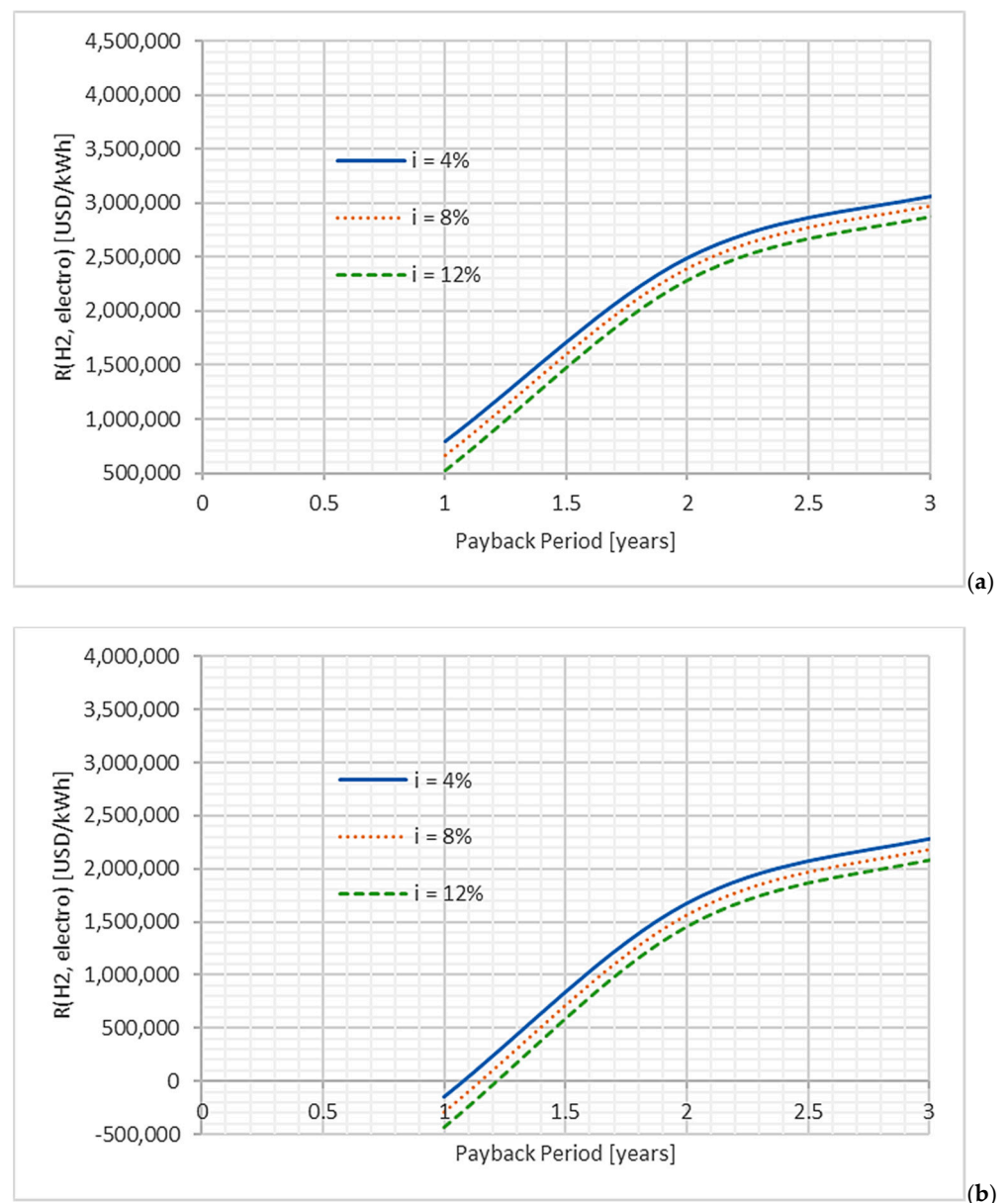


Figure 18. Expected annual income of the biohydrogen production using the bioelectricity from motor/generator set with the power supplied by the plant. (a) São José da Estiva. (b) São Manoel.

4. Discussion

From the energy analysis, although the global efficiency of the system is relatively low at 16.14%, when each part of the system is evaluated separately, the perspective changes. As explained earlier, internal combustion engine systems running on biogas do not have an electrical efficiency exceeding 30%, so it was expected that a significant portion of the energy would not be utilized. This can be compensated by integrating a system that captures the lost energy, such as a cooling system or a heat exchanger, among others. On the other hand, when evaluating the efficiency of the electrolyzer, it is found to be 60.39%, meaning that most of the bioelectricity is used for biohydrogen generation.

With the system running 7300 h a year, and considering annual interest rates ranging of 4, 8, and 12%, throughout a 25-year period of the implementation of the system, it is shown in Figure 15 that the cost of producing bioelectricity, C_{elICM} , went from 0.08 USD/kWh in the first year to 0.03 USD/kWh in the fourth year and finally reaching a stable price of 0.02 USD/kWh from the seventh year onwards for the São José da Estiva plant, and went from 0.09 USD/kWh in the first year to 0.03 USD/kWh in the fifth year and reaching

a constant price of 0.02 USD/kWh from the eighth year onwards, for the São Manoel plant. If it is considered that the cost of electricity supplied by the grid for industries is 0.145 USD/kWh, even with a low electrical efficiency of 26.73% for the motor/generator set, the cost of generating bioelectricity with the set is remarkably low. The expected annual income by the payback method, considering only the bioelectricity production system as shown in Figure 16, indicates that the initial investment in the motor/generator set is recovered before the first year for both plants. Therefore, implementing a bioelectricity generation system using vinasse biogas is highly viable in any sugar and alcohol plant. This could lead to increased revenue if the decision is made to sell the surplus energy generated rather than using it for biohydrogen production, as proposed in this study.

In Figure 17, the cost of producing biohydrogen, $C_{H_2, electrolyzer}$, for the São José da Estiva plant starts at 0.24 USD/kWh (4%), and 0.25 USD/kWh (12%) in the first year, goes to 0.07 USD/kWh (4%) and 0.08 USD/kWh (12%) by the fifth year, and by the tenth year it will reach 0.05 USD/kWh (4%) and 0.06 USD/kWh (12%). For the São Manoel plant, it will start at 0.30 USD/kWh (4%) and 0.32 USD/kWh (12%) in its first year, 0.08 USD/kWh (4%) and 0.10 USD/kWh (12%) in the fifth year, and reach 0.06 USD/kWh (4%) and 0.07 USD/kWh (12%) at the tenth year. Both plants reach the commercial price for hydrogen between the first two years of the system implementation.

From Figure 18, it is clear that for the complete process, now considering the biohydrogen production also, the time of return of the investment in the motor/generator set and the electrolyzer increases a little, for the São José da Estiva plant, the return will occur before the first year, having an annual income of 792,839.23 USD (4%) and 525,352.32 USD (12%), reaching 3,888,501.96 USD (4%) and 3,678,407.29 USD (12%) after the tenth year. For the São Manoel plant, the return on the investment occurs after the second year, having an annual income of 1,670,496.85 USD (4%) and 1,450,832.33 USD (12%), and reaching an income of 3,123,824.69 USD (4%) and 2,932,050.63 USD (12%) by the end of the tenth year. Considering that these values are reflecting that the electrolyzer is working only with the bioelectricity produced by the motor/generator set and not taking any electricity available from the general supply network, it can be inferred that this proposed system, working 7300 h every year, can be viable for this type of sugar and ethanol plant. Also, it is good to state that in both cases, the initial investment was recovered before the second year of use after the implementation.

5. Conclusions

The results of the energy and economic analysis of the proposed system were assessed to determine its feasibility for implementation in the two plants studied. Firstly, it can be stated that the system is self-sustaining, as it relies solely on a product that is already part of the plant's process: vinasse, a by-product of ethanol distillation. Secondly, the percentage of vinasse used for bioelectricity generation was 100% of the total production, meaning that the goal of obtaining a useful energy source by taking advantage of vinasse, was hit. Furthermore, it should be noted that most sugar mills generate their own electricity, either through the combustion of bagasse or other processes. In the proposed system discussed in this study, this internal electricity generation was not considered; the evaluation was based solely on the bioelectricity generated by the motor/generator set to power the electrolyzer and produce biohydrogen. The analysis also revealed that the initial investment for implementing the system is recovered long before the proposed 25-year operational period, with a minimum payback time of 1 year for the São José da Estiva plant and 2 years for the São Manoel plant. This makes the system viable for installation in other sugar and ethanol mills with production levels similar to those of the studied plants, which ranged from 130,000 to 160,000 m³/year of ethanol.

In conclusion, the process of obtaining biohydrogen through electrolysis, using 100% of the total vinasse production from both plants (São José da Estiva and São Manoel), represents a viable investment in the short, medium, and long term, even without accounting for the electricity generated by the plant. For future work, several factors should be consid-

ered, such as evaluating a similar hydrogen production system using alternative fuels, like sugarcane bagasse combustion, or implementing the system in other types of plants, such as those producing corn or beets, which are also quite common in Brazil. Additionally, it is essential to implement a system to recover lost thermal energy, whether through a heat exchanger to generate hot water and additional energy, or an absorption refrigeration system to produce chilled water. However, the most important consideration for future work will be the implementation of the system while also factoring in the co-generation of energy from the plants themselves. It can be inferred that the costs of energy and biohydrogen generation, as well as the return on investment, will be significantly better for the mills that choose to adopt this system.

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Nomenclature

C	Estimated cost for plant implementation [USD]
C_{ele}	Cost of electricity for industrial processes [USD/kWh]
$C_{electrolyzer}$	Cost of electrolyzer [USD]
C_{elICM}	Cost of bioelectricity produced by the motor/generator set [USD/kWh]
C_{fuel}	Cost of fuel [USD/kWh]
C_{H_2}	Cost of biohydrogen in the market [USD/kWh]
$C_{H_2electrolyzer}$	Cost of biohydrogen production by electrolysis [USD/kWh]
C_{H_2O}	Cost of water supplied [USD/kg]
$C_{man_{electrolyzer}}$	Maintenance cost of the electrolyzer [USD/kWh]
$C_{man_{ICM}}$	Maintenance cost of the motor/generator set [USD/kWh].
$C_{op_{electrolyzer}}$	Electrolyzer operating cost [USD/kWh]
C_R	Reference cost of the equipment [USD]
E_{egtp}	Exhaust gas thermal power [kW].
E_{fuel}	Power supplied by the fuel [kW]
E_{H_2}	Power supplied by the biohydrogen [kW]
E_{pICM}	Power produced by the motor/generator set [kW]
$E_{req_{elec}}$	Power required by the electrolyzer [kW]
E_{STP}	Single thermal power variable [kW]
E_{ttp}	Transferred thermal power [kW]
f	Annuity factor [1/year]
H	Working period of the motor/generator set [hours/year]
h_{air}	Enthalpy of air at 25 °C [kJ/kg]
k	Payback period [years]
i	Annual interest rate [%]
I_{pICM}	Investment in the motor/generator set [USD]
$I_{electrolyzer}$	Investment in the electrolyzer [USD]
LHV_{fuel}	Low heat value of fuel [kJ/kg]
LHV_{biogas}	Low heat value of biogas [kJ/kg]
LHV_{H_2}	Low heat value of biohydrogen [kJ/kg]
$Losses$	power lost in the system [kW]

m	Correction factor to determine the estimated cost, between 0.5 and 1
m_{air}	Air mass flow [kg/s]
$m_{biogasP}$	Mass flow rate of Biogas supplied [m ³ /h]
$m_{biogasICM}$	Mass flow of biogas in the motor/generator set [kg/s]
m_{fuel}	Mass flow of fuel [kg/s]
m_{H_2}	Mass flow of biohydrogen produced [kg/s]
m_{H_2O}	Mass flow of water in the electrolyzer [kg/h]
$\eta_{electrolyzer}$	Electrical efficiency of the electrolyzer [%]
η_{elICM}	Electrical efficiency of the motor/generator set [%]
$\eta_{elec.elICM}$	Electrical efficiency of the entire process [%]
ρ_{biogas}	Specific mass of the vinasse biogas [kg/m ³]
P_{H_2}	Biohydrogen production capacity [Nm ³ /h]
S	Specification of the equipment [-]
S_R	Reference of a specification for the required system [-]
R_{H_2}	Expected annual income from the H ₂ production based on payback [USD/kWh]
R_{ICM}	Expected annual income from the electricity production based on payback [USD/kWh]

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