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Economic and Environmental Assessment of Hydrogen Production from Brazilian Energy Grid

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Abstract: The Brazilian energy grid is considered as one of the cleanest in the world, because it is composed of more than 80% of renewable energy sources. This work aimed to apply the levelized costs (LCOH) and environmental cost accounting techniques to demonstrate the feasibility of producing hydrogen (H_2) by alkaline electrolysis powered by the Brazilian energy grid. A project of hydrogen production, with a lifetime of 20 years, had been evaluated by economical and sensitivity analysis. The production capacity (8.89 to 46.67 kg H_2/h), production volume (25 to 100%), hydrogen sale price (1 to 5 USD/kg H_2) and the MAR rate were varied. Results showed that at 2 USD/kg H_2, all H_2 production plant sizes are economically viable. On this condition, a payback of fewer than 4 years, an IRR greater than 31, a break-even point between 56 and 68% of the production volume and a ROI above 400% were found. The sensitivity analysis showed that the best economic condition was found at 35.56 kg H_2/h of the plant size, which generated a net present value of USD 10.4 million. The cost of hydrogen varied between 1.26 and 1.64 USD/kg and a LCOH of 37.76 to 48.71 USD/MWh. LCA analysis showed that the hydrogen production project mitigated from 26 to 131 thousand tons of CO_2, under the conditions studied.

Keywords: hydrogen production; energy grid; environmental cost accounting; levelized cost of hydrogen; carbon credit

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1. Introduction

Energy consumption is closely linked to the amount of CO_2 emissions in a country, especially when using fossil and non-renewable sources. Water, wind, solar, hydrogen, biogas, ethanol and biodiesel are considered as important energy options as a substitute for fossil fuels, as they are renewable resources and endless. The current belief is that replacing fossil fuels with these renewable sources can reduce the emissions of greenhouse gases (GHG), and it is a highly profitable investment [1–3].

In the European scenario, the incentives for renewable energies raised the share of wind and solar energy to 24% in the share of the mix of the European energy matrix. In the American scenario, renewable energies correspond to 10.4% of the American energy mix. With more than 300,000 TW of capacity, wind energy currently has the largest share of renewable energies. The energy planning of large consumers indicates a worldwide trend towards the diversification of the energy matrix. The Brazilian scenario also presents increasing investments in wind power generation. At the beginning of 2015, Brazil had 6.0 GW of installed wind power and, due to the Brazilian government's planning, this value reached 22 GW in 2022 [4,5]. This improvement in the scenario was due to the excellent conditions, which are favored due to the higher values of the quarterly average speed ranging from 6 to 8 m/s [6].

Currently, the world is focused on developing ways to produce hydrogen. Mazzeo et al. [7] simulated wind and solar systems, or hybrid ones, for green hydrogen production worldwide using TRNSYS, which was analyzed using MATLAB and Excel. Results showed that the applied procedure can be easily used to test small-scale applications, such as residential users, or large-scale applications, such as industrial users, as well as for any hydrogen demand and climatic conditions. Herdem et al. [8] modelled and simulated a combined biomass gasification-solar photovoltaic hydrogen production system for methanol synthesis via carbon dioxide hydrogenation in Canada and Italy. Their results showed that for both localities, the best energy performance that minimizes the grid energy interaction factor is obtained with a photovoltaic station of 50.4 MW coupled to biomass gasification, which leads to 0.585 kWh of electricity sent to or drawn from the grid for each kWh required by the electrolyzer and a profit of EUR 0.50 M with a single biomass gasification system.

Global solar radiation values occurring in any region of Brazilian territory (4200–6700 kWh/m^2) are higher than in most European Union countries, such as Germany (900–1250 kWh/m^2), France (900–1650 kWh/m^2) and Spain (1200–1850 kWh/m^2). In this sense, Brazil was the 4th country in the world that most added photovoltaic solar capacity in 2021, with a new 5.7 GW in the last year [4].

Anthropogenic emissions in 2021 associated with the Brazilian energy matrix reached 445.4 million t CO_2 equivalent, which is 12.4% higher than in 2020 and a 54.4% increase compared to 20 years ago. Even so, the Brazilian per capita emission is 1.9 t CO_2 eq, which is equivalent to 13% of an American, 32% of a European and 27% of a Chinese citizen. This occurs because the Brazilian energy mix is composed of more than 80% of renewable energy resources [6]. However, this could be improved if hydrogen were in the Brazilian energy grid, as it is a fuel that has zero direct CO_2 emissions.

Currently, the Brazilian government is trying to implement H_2 production using renewable energy and the power grid. In line with this idea, the concept of large-scale hydrogen generation hubs is recognized as a key strategy in Brazil. Thus, it is essential to explore a wide range of input assumptions to identify key cost drivers, targets and localized conditions necessary for competitive stand-alone dedicated H_2 production [9–11].

Thus, this work aimed to verify the feasibility of hydrogen production projects using energy from the Brazilian grid. The economic, environmental and social advantages are also presented in project summaries. A project of hydrogen production with a lifetime of 20 years had been evaluated using economical and sensitivity analysis. The plant size, production volume, H_2 sale price and the minimum attractive rate were varied to find the best design conditions. The results that presented can be applied in any Brazilian region, as they are using their energy grid.

1.1. Electric Panorama of Brazil

The national operator of the Brazilian electric system (ONS) is responsible for controlling the energy distribution network in Brazil (the Brazilian grid) [12]. ONS activates the power plants and distributes electricity to all Brazilian states, using the grid shown in Figure 1. This figure shows a map of the current smart grid of the Brazilian electric system. According to Guerhardt et al. [4] and Schio [13], the power distribution networks are composed of hydroelectric, thermoelectric, solar and wind power plants, which are interconnected in a smart grid with five distribution systems (Paraná, Paranapanema, Grande, Paranaíba and Paulo Afonso).

Since the 1990s, the Brazilian power utility company, Electrobras is responsible for managing the distribution and sale of electricity on the Brazilian grid to local distribution companies (LDC), which then distribute it to consumers [12]. This same management system, through Law 13,673, also obliges LCD companies to provide the history of readjustment of energy tariffs. Currently, the energy tariff charged to industries in Brazilian northeast is 68.58 USD/kWh [14]. In São Paulo, 133.70 USD/MWh is charged for industries, and according to Federation of Industries of Rio de Janeiro [15], the national average cost of electricity for Brazilian industries was 93.68 BRL/MWh. However, the sale of energy to distribution companies takes place in the auction and its average price was 30.77 USD/MWh [14,15].

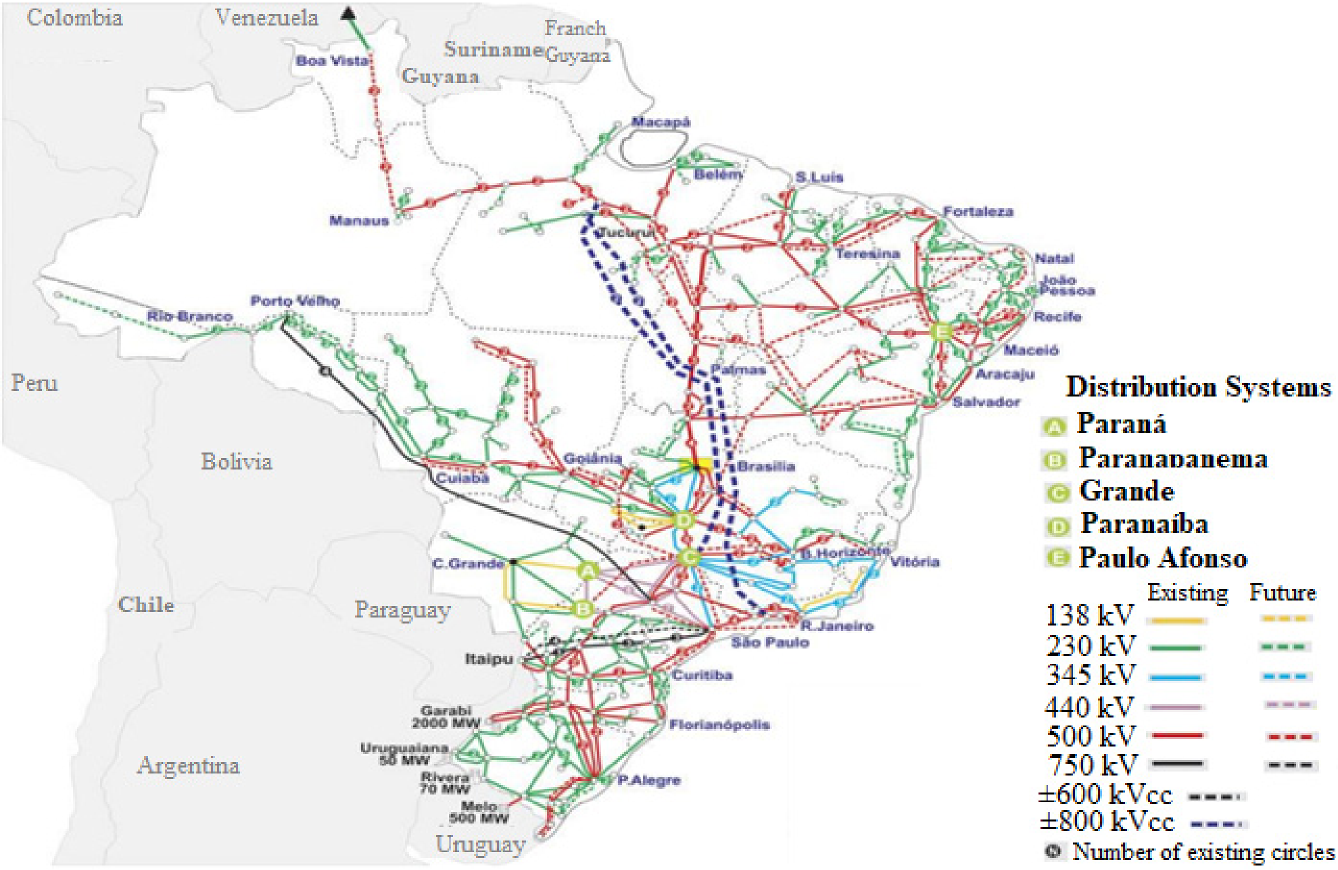

Figure 1. Scheme of smart grid of the Brazilian electrical system [4,13].

For Guerhardt et al. [4], Ouyang et al. [16] and Zhang et al. [17], the use of the smart grid in the Brazilian electrical system has contributed to significant progress in the updating and improving the power supply company to make it more modern in terms of functionality and architecture. This would ensure grid reliability by controlling the continuous flow of energy in the best way to customers, and if deployed worldwide, it would adjust electric energy consumption to decrease CO_2 and other pollutant gaseous emissions, minimizing the greenhouse effect and the effects of climate change and increasing energy security.

Table 1 shows the contribution of each energy sources in the installed capacity of the Brazilian electrical system. The renewable sources are hydro, wind, solar and biomass. The latter is very diversified, from sugarcane bagasse to biogas from organic waste and landfills. From 2017 to 2021, the generation of electricity from renewable sources ranged from 81 to 86% in Brazil. The expectation is that this percentage will increase in 2022 and, thus, CO_2 emissions will be reduced [5].

Table 1. Participation of energy sources in the installed capacity [12].

Source/Year	2017	2018	2019	2020	2021
Hydro	65.0	64.0	64.6	64.5	56.8
Wind	8.0	8.8	9.5	8.7	10.6
Solar	0.6	1.1	1.6	1.6	2.5
Biomass	9.1	9.1	8.6	11.7	11.6
Thermal *	16.1	15.8	14.5	11.3	16.3
Nuclear	1.2	1.2	1.2	2.2	2.2

* Thermal: natural gas, diesel oil, coke and other petroleum derivatives.

However, thermal source of electricity used in Brazilian thermoelectric plants are derived from non-renewable resources, such as natural gas, diesel oil and other petroleum derivatives. The use of non-renewable sources is linked to the activation of thermoelectric plants, which is closely linked to the reduction of water reservoir levels in hydroelectric dams [6].

Figure 2 shows the variation in the use of thermoelectric plants operating exclusively with non-renewable sources in the entire national integrated system in Brazil (Brazilian Grid). As noted, throughout this period, the Brazilian grid uses non-renewable sources, changing only amount [12]. According to the government, Brazil's need for thermoelectric energy in 2022 will be lower than last year; instead of having a share of 16.3%, it will only account for 4.9% of the installed capacity. In this way, the prediction of the participation of renewable sources will exceed 90% in 2022. However, these sources make it impossible to produce green hydrogen using electricity directly from the Brazilian grid [18]. Using a mix of renewable and fossil energies, it is only possible to obtain yellow hydrogen.

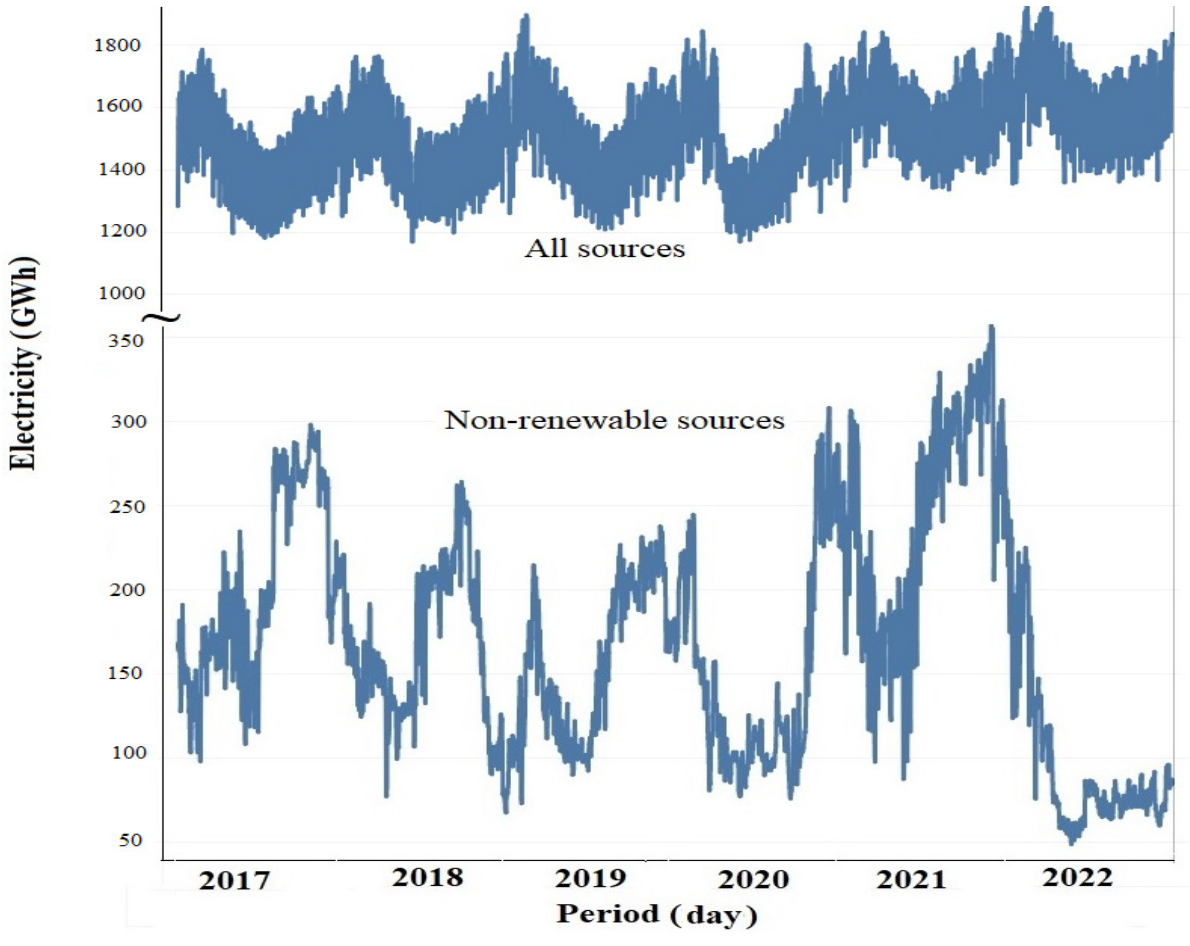

Figure 2. Thermal participation into Brazilian energy sources in the current installed capacity [12].

1.2. Hydrogen Production in Brazil

In this sense, research on ways to produce and make hydrogen production economically viable is currently being encouraged. In recent years, the hydrogen market has become a priority in the climate and energy strategy of several countries, as it provides an alternative for sectors that are difficult to reduce carbon emissions. In addition, hydrogen is also an energy vector, which enables storage and favors the coupling of the energy sector with those of industry and transport [6]. Thus, the demand for hydrogen in the world is increasing year by year.

According to Suleman et al. [19], the leverage search for hydrogen occurs because of the following advantages:

- H_2 is a high-quality energy carrier, which can be used at high efficiency with zero or near zero emissions;
- During combustion with air or when used in a fuel cell to generate electricity, only water is produced;
- It has been technically proven that hydrogen can be used for transportation, heating, and power generation and could replace current fuels in all their present uses;
- It exhibits the highest heating value per mass among all chemical fuels (141.9 kJ/kg or 33.61 kWh/kg) and is regenerative and environmentally friendly;
- It has attractive electrochemical properties, which can be utilized in a fuel cell;
- It can be stored in different forms, such as in a gaseous form suitable for large-scale storage, in a liquid form, which is suitable for air and space transportation, or in the form of metal hydrides to be convenient for small-scale storage requirements [19].

In this sense, the National Energy Policy Council (CNPE) of Brazil published Resolution No. 6, of 23 June 2022, which instituted the National Hydrogen Program (PNH2) and established the program's governance structure. Since 2021, other decisions by the Brazilian government have already identified the strategic role that hydrogen can play in a future of decarbonized economies, defining hydrogen as one of the priority topics for investments in research and development [6].

To date, the following methods exist for the production of hydrogen:

- Steam reforming of natural gas (SRNG) is the most popular method of H_2 production. In a typical steam reformation process, a hydrocarbon is desulphurized and fed into a reforming unit along with superheated steam from demineralized water and in the presence of a catalyst, steam and the fuel gas are converted to a H_2-rich reformate [20]. This is the most used method in the world, including Brazil.
- Another traditional process is the coal gasification process, in which a gasifier, a reaction between the coal, O_2 and steam under high pressures and temperatures results in a syngas that is a mixture of H_2, CO, CO_2 and sulfur compounds. Hydrogen gas gets separated by compression and stored or transported [20].
- The latest methods are membrane cell electrolysis. The cell is separated into two sections by a membrane that performs as an ion exchanger. Initially, the ionic compartment is filled with saturated salt brine and the cathode department is filled with only water. The main advantages of this membrane type electrolysis is that its moderate energy consumption is almost less than the diaphragm cell, more pure sodium hydroxide is produced in this technology as compared to the diaphragm cell with very small amounts of environmental impacts [21]. According to Avargani et al. [20], the four main types of electrolysis cells used for H_2 product are the alkaline electrolyzer (AE), polymer electrolyte membrane electrolyzer (PEME), high-temperature solid oxide electrolyzer (SOE) and molten carbonate electrolyzer (MCE). The Brazilian government intends to use these techniques in its national hydrogen production plan.

Brazil produced 6.3 billion Nm^3/year (m^3 under normal conditions of temperature and pressure) of hydrogen in 2015, which has been reduced to less than 5 billion Nm^3/year of hydrogen in recent years. The company Brazilian Petroleum S. A. (Petrobras) accounts for approximately 95% of the total production in the country, which corresponds to 4.5 billion of Nm^3/year. This production is carried out exclusively by steam reforming of natural gas, which turns the hydrogen gray [18,22]. The remaining portion of the national production of hydrogen, are produced by the industrial gas industries, which produce hydrogen for use in the industrial, medicinal and protective fields. In addition to these, hydrogen can be used in the petrochemical, steel, metallurgy, food, ceramics and glass industries, as well as in power generation [22].

Hydrogen, although a renewable energy source, is not yet part of the Brazilian energy grid. This same matrix that makes up the electricity grid makes the production of green hydrogen unfeasible, as it uses non-renewable sources [18]. However, it is possible to assign carbon credits in the production chain of this hydrogen because most energy sources are clean. Thus, a life cycle assessment (LCA) for each of the energy sources and weighting their influences on CO_2 emissions per unit of hydrogen produced can result in assigning carbon credits.

1.3. Life Cycle Assessment in Renewable Energy Production

In the last decades, research for a fuel that is renewable, healthful and technically and economically viable has grown considerably in intensity worldwide [1,11,23,24]. Therefore, there is an incentive to use renewable sources to supply energy for traditional hydrogen production techniques. However, the selling price of hydrogen produced using only renewable sources is one of the main barriers faced by this fuel [21,25].

Cetinkaya et al. [26] developed LCAs for the five methods of hydrogen production, namely steam reforming of natural gas, coal gasification, water electrolysis via wind and solar electrolysis and thermochemical water splitting. Carbon dioxide equivalent emissions and energy equivalents of each method are quantified and compared. Results showed that, in terms of hydrogen production capacities, natural gas steam reforming, coal gasification and thermochemical water splitting methods were found to be advantageous over the renewable energy methods.

However, other research has been developed using LCA methods to show the economic and environmental feasibility of producing energy from renewable sources. This was showed by Moraes et al. [27], who evaluated the vinasse anaerobic digestion in biorefineries in terms of energy, environmental and economic considerations. The energy potential from the vinasse of a single sugarcane biorefinery, which is generally lost due to its application to soil with no treatment, was found to be comparable to the electricity supply demand of a city of approximately 130,000 inhabitants or to the surplus energy from bagasse burning that is exported by some sugarcane mills in Brazil. On a national level, such energy is comparable to the electricity generated by some hydroelectric plants, reaching 7.5% of the electricity generated by the world's largest hydroelectric plant.

Ribeiro et al. [28] had developed a LCA of the Itaipu Hydropower Plant, responsible for producing 23.8% of Brazil's electricity consumption. This study was focused on the capital investments to construct and operate the dam, to serve as a database for the LCAs of Brazilian hydroelectricity production. The life cycle boundaries encompass the construction and operation of the dam, as well as the life cycles of the most important material and energy consumptions, as well as construction site operation, emissions from reservoir flooding, material and workers' transportation and earthworks for 100 years. As a result, besides the presented inventory, the values of matter and energy consumed per functional unit were compatible with the results presented in the literature and greenhouse gas emissions (GHG) 4.33 kg CO_2 eq/MJ.

The Swedish Environmental Management Council, SEMC [29] also found results between 5 and 11 kg CO_2 eq/MJ when performing the LCA analysis of two hydropower plants. Liu et al. [30] had developed the LCA analysis of 34 Chinese hydropower plants and found a carbon footprint ranged from 5.43 to 49.36 g CO_2-eq/kWh, while the imputed GHG emissions. Zang et al. [31] compared the carbon footprints of two Chinese hydropower sources using the LCA method. Results showed that emission factors were between 8.36 and 11.11 g CO_2 eq/kWh in the 44 years of operation of the plants. Gemechu and Kumar [32] reported a huge range of emissions values is reported in the reviewed literature, from 1.5 to 3747.8 g CO_2 eq per kWh and claim that such variations are due to failures in the analyses, as the reservoir GHG emissions could be more than 90% of the life cycle emissions, especially for hydropower in a tropical region.

2. Materials and Methods

Table 1 shows the complexity of Brazilian energy grid is to make its lifecycle assessment (LCA), because, it is composed of renewable energy sources, such as water, biomass, wind, solar, coal, diesel oil, natural gas and uranium. Thus, the methods and results will be presented briefly. The variables used in the analyses will be presented in each of the methodology items, mainly in the form of equations.

2.1. Alkaline Electrolysis of Water

The hydrogen production plant was composed of electrolysis kit(s), composed of a polymer electrolytic membrane electrolyzer (PEME), with compressors and storage tanks for H_2 and O_2. In this electrolytic cell, a diaphragm separates the two anode and cathode electrodes, where direct current is used in the cell. H_2 is produced at the cathode and O_2 at the anode electrodes. Usually a concentrated solution (25–30% KOH by weight) is used as an alkaline solution to maximize ionic conductivity. The global reaction of this process is shown in Equation (1) [16–21]. The complete kit costs USD 500,000 and is capable of producing up to 100 Nm^3/h (8.89 kg/h) of H_2 [33].

$$2\,H_2O_{(l)} \leftrightarrow 2\,H_{2\,(g)} + O_{2\,(g)} \tag{1}$$

Allocation of the hydrogen production plant should be as close to highways and rivers to facilitate the flow of production. For the production of each 1 kg H_2, it is estimated that the water consumption is 23 L and the energy consumption is 27 kWh, including other consumptions inside and outside the production process. Each 1 m^3 of gaseous H_2 contains 8.89 kg of the same gas.

Therefore, the H_2 production capacity (CP_{H_2}) of plants were increased by varying the amount of electrolysis kits, such as in Equation (2). From these compositions, the flows of material, energy and emissions were determined [26–28].

$$PC_{H_2}(\mathrm{kg/year}) = 77{,}876.4 * E_n \tag{2}$$

where E_n is amount of electrolysis kits. The constant in this equation is the result of multiplying the H_2 flow by the number of annual hours. Due to the stoichiometry of the reaction, the production of oxygen is proportional to the H_2. O_2 was sold in cylinders containing 10 m^3, then, the ideal gas laws were applied resulting in Equation (3).

$$PC_{O_2}(\mathrm{cylinders/year}) = 5.5965 * PC_{H_2} \tag{3}$$

2.2. Life Cycle Assessment of H_2 Production

For the life cycle analysis, the production of hydrogen from the steam reform of methane will be used as a comparative basis, as it accounts for 95% of Brazilian production. All materials and energy consumed and direct and indirect emissions from production vary with the volume of H_2 produced (Equation (1)).

As the electrical energy consumed in the production of H_2 will be derived from the Brazilian grid, which is composed of several sources, the contribution of each energy source was weighted, and the results were presented as a weighted average of these emissions, such as in Equation (4).

$$Emission = PC_{H_2} * \left\{ \frac{\sum_{i=1}^{n} f_i * X_i}{\sum_{i=1}^{n} f_i} \right\} \tag{4}$$

The weightings (f_i) were considered as the percentage of each energy source (x_i) in the Brazilian grid, as shown in Table 1.

The raw material, energy and emissions flow data were obtained from the companies' websites and from the literature on the specific topic, and the calculations of the emissions and material flow were obtained based on the Brazilian GHG Protocol Program, generating a flow inventory of material and direct and indirect emissions per unit of H_2 produced based on the top-down methodology [19,34]. All CO_2 emissions will be converted into carbon credits that will be used as a source of improving environmental sustainability and corporate image, as well as in the composition of corporate profits [35]. Data of the life cycle assessment of hydrogen plants were provided by [19,26–28,36].

Based on the energy sources and processes used to obtain it, hydrogen will be classified in colors from the most sustainable to the least sustainable, as presented in [17].

2.3. Life Cycle Costing (LCC)

LCC is an important method to evaluate the total cost of a product or a system over its given lifetime. However, due to the criticism, only its holistic part will be addressed in this research. The opportunity costs with carbon credits, with the reduction of taxes due to good environmental and social practices, the use of renewable energies and the levelized cost of hydrogen will also be calculated and presented during all periods of the hydrogen production life cycle.

The use of hydrogen is associated with a 100% reduction in CO_2 emissions. This conversion of the energy consumed (or surplus of energy) to carbon credits would be performed using the Official Carbon Credits Calculator developed by the Brazilian GHG Protocol and certified by the LRQA Business Assurance [1,2,6,11]. However, as there are emissions during its production and use chain, carbon credits (CC_{H_2V}) will be calculated by reducing emissions compared to the Brazilian hydrogen production cycle, which is based exclusively on steam reforming of natural gas (SRNG). Thus, it was calculated by the subtraction of the emissions from both processes, as shown in Equation (5):

$$CC_{H_2}(\text{ton } CO_2) = CO_{2\ \text{SRNG}} - CO_{2\ H_2} \tag{5}$$

where $CO_{2\ \text{SRINGl}}$ and $CO_{2\ H_2}$ are the amount (in tons) of CO_2 produced in the H_2 production life cycles by the SRNG technique and electrolysis using electricity from the Brazilian grid.

The profit associated with the sale of the carbon credits could be obtained using Equation (6), as follows:

$$\text{CC revenue (US\$)} = \text{ton}CO_2 \times \text{Current Price (US\$/ton}CO_2) \tag{6}$$

Currently, each carbon credit is sold on the futures market for USD 30 and the conversion is that each USD 1 is equivalent to BRL 5.20 [35]. However, it was considered only as a financial asset for gains in the future market, and thus, it was not considered in the financial analysis of the projects.

2.4. Description of Financing Project Conditions

Each H_2 electrolysis kit costs USD 500,000 and produces 100 m^3 of H_2/h (8.89 kg/h). The national average energy cost was used, which is 30.769 USD/MWh and the water cost was 4.91538 BRL/m^3, supplied for LCD companies. As H_2 production in Brazil is close to 400,000 t/year [22], more than 5100 electrolysis kits would be needed to supply the entire Brazilian production. Therefore, in the simulations presented in this work, the production capacity was varied in order to simulate the performance of small production plants, with 1, 2, 3, 4 and 5 electrolysis kits, corresponding to the range of 8.89 to 44.5 Nm^3 H_2/h. Plant maintenance was considered equal to 4% of the equipment's annual depreciation value [2,9,11,24].

The financing was requested from National Bank for Economic and Social Development [2,9,37], in the Prime table, for 20 years (n), at a rate of 1.17% p.a. (i). The amounts financed varied according to the costs of 100% production capacity, and working capital was added to help the company pay all expenses for the first year. Initial investment (I) was given to Equation (7).

$$I(\text{U\$S}) = E_n * KitCost(\text{US\$}) + \text{Working capital} \tag{7}$$

Total annual cost was considered as working capital.

2.4.1. Environmental Cost Accounting Strategies

Activity-based costing (ABC costing method) was the accounting method used in this work. The allocation of activity costs to products is carried out using a specific apportionment criterion for each activity (cost drivers).

A structured procedure was used to assess the feasibility of investments, based on the cash flow (CF) method. That makes an accounting balance in each period of the project, to obtain the profits by subtracting the costs and expenses of the revenues associated with the products. For the development of the balance sheets, the ABC strategies were used, considering that the prices of products were motivated by the costs associated with production and the profit desired by the company [2,9,24].

In the composition of the fixed cost, the costs are the installation and environmental fees of the plant, financial parcel (I_n), maintenance (M_n) and wages [1]. According to the Prime table, the financial parcel (I_n) is given by Equation (8):

$$I_n(\text{U\$S/year}) = \left(\frac{I * i((1+i)^n}{(1+i)^n - 1}\right) \tag{8}$$

The plant depreciation will be considered as the value of the electrolytic kits divided by the useful life of the project, then the maintenance (M_n) cost was given by Equation (9):

$$M_n(\text{U\$S/year}) = 0.04 * \left(\frac{E_n * KitCost(\text{US\$})}{n}\right) \tag{9}$$

where n is the useful time of financing project, and E_n is number of electrolytic kits used in the plant.

A 7% state taxes on revenue and 8% income tax levied on real profit was considered. Up to 6% of the income tax amount was used in the social projects in the region. Social charges levied on wages were 68.17%, as governed by Brazilian labor law [2,9,37].

The costs that vary with the production volume were considered to be the water and energy costs consumed in the process. Water consumed in the plant will be supplied at the rate of 23 L for each 1 kg of H_2 produced and already counting the water consumed in production and in the other sectors of the plant [38]. Approximately 60.87% of the input volume is left as wastewater with a concentration of 1.64 of each substance present. The cost with the acquisition of electricity from the Brazilian energy grid was calculated using the factor of 27 kWh/kg H_2, which is the amount of energy consumed in all sectors of the plant to produce 1 kg of H_2 [38]. As water and electricity depend on H_2 production, the variable costs can then be obtained by Equation (10).

$$\text{VC}(\frac{\text{US\$}}{\text{year}}) = \text{P}_{\text{H}_2}(\text{kg}) * \left(23\ (\frac{\text{m}^3}{\text{kg}}) * \text{SP}_{\text{H}_2\text{O}}\left(\frac{\text{US\$}}{\text{m}^3}\right) + 27(\frac{\text{kWh}}{\text{kg}}) * \text{SP}_{\text{Energy}}\left(\frac{\text{US\$}}{\text{kWh}}\right)\right) \tag{10}$$

The total annual cost was calculated adding the financing parcel, wages (W_n), maintenance (M_n) and all taxes and variable costs, as in Equation (11).

$$\text{Total annual } \cos \text{t}(\text{US\$/year}) = \text{VC} + \text{I}_\text{n} + \text{M}_\text{n} + \text{W}_\text{n} + \sum \text{tax} \tag{11}$$

Revenues were provided by the sale of the main product (H_2) and its by-product (O_2). According to Brazilian regulations, hydrogen must be compressed to 220, 350 or 700 bar and transported exclusively via road transport. As the sale price of common H_2 varies between 1.32 and 3 USD/kg, the selling price, simulated in this research, was varied in this range [6,25,37,38].

It is intended to sell compressed O_2 to hospital gas companies. O_2 was filled into 70 L cylinders containing 10 Nm^3 and sold for a fraction of the commercial hospital oxygen price (5–22 USD/Nm^3) [39]. All simulations had been using a hospital O_2 price of 5 USD/cylinder with 10 Nm^3, which is 10% of the commercial selling price. On the other hand, the company is responsible for collecting the O_2 bottle.

As the cash flows were developed annually, many costs and expenses were considered to be fixed. However, the volume of water and energy consumed during production are variable costs. Unit costs are obtained by dividing these values by the production volume. Thus, we will have fixed (FUC) and variable (VUC) unit costs and the sum of these generates the total unit cost (UC), obtained using Equation (12), below.

$$\mathrm{FUC}(\mathrm{US\$/kg}) = \left(\frac{\mathrm{FC}}{\text{Production volum}}\right) \tag{12a}$$

$$\mathrm{VUC}(\mathrm{US\$/kg}) = \left(\frac{\mathrm{VC}}{\text{Production volum}}\right) \tag{12b}$$

$$\mathrm{UC}(\mathrm{US\$/kg}) = \mathrm{FUC} + \mathrm{VUC} \tag{12c}$$

To calculate the sale price, Equation (13) was used.

$$\mathrm{SP}(\mathrm{US\$/kg}) = \left(\frac{\mathrm{UC}}{1 - \text{markup}}\right) \tag{13}$$

where FC and VC are fixed and variable costs, respectively, and the markup was considered the company's taxes and profit margin.

Product sales revenue was calculated using production volumes (P_{H_2} and P_{O_2}) and product sales prices, as shown in Equation (14). When the production capacity (PC) is 100%, the production volume (P) is equal to the production capacity, given by Equation (14). For lower percentages, the volume will be a fraction of the production capacity [2,9].

$$\mathrm{Revenue}(\mathrm{US\$}) = P_{H_2}(\mathrm{kg}) * SP_{H_2}\left(\frac{\mathrm{US\$}}{\mathrm{kg}}\right) + P_{O_2}(\text{cylinder}) * SP_{O_2}\left(\frac{\mathrm{US\$}}{\text{cylinder}}\right) \tag{14}$$

where SP_{H_2} and SP_{O_2} are the H_2 and O_2 selling prices, respectively.

From these equations, the accounting result is obtained using Equation (15), as follows:

$$\mathrm{Result}(\mathrm{US\$}) = \mathrm{Revenue}(\mathrm{US\$}) - \text{Total Cost }(\mathrm{US\$}) \tag{15}$$

The result of the balance sheet when positive is called profit and when negative is called loss. When the data used in Equation (16) are time varying, this equation can also be called cash flow.

2.4.2. Sensitivity Analysis

To understand the risks associated with the project, a sensitivity analysis was applied. Therefore, some economic parameters were varied in relation to production volume, project time and attractiveness rates. Thus, after obtaining the cash flows, sensitivity analyses were applied to the data to verify which risk conditions the plant may be subject to. Ratios, such as rates of return on investment (IRR), net present values (NPV), return on investment (ROI), payback and break-even points will be used to determine which project was the most viable [2,9,24].

To measure the quantity of products sold that start the company's profit, the break-even point (BP) was calculated, according to Equation (16). The farther the company's production capacity (volume) is from the break-even point, the more the company is economically sustainable.

$$\mathrm{BP}(\text{unity}) = \frac{\text{Total fixed cost}}{SP_{H_2} * S_{H_2} + SP_{O_2} * S_{O_2}) - \mathrm{VUC}} \tag{16}$$

where VUC is the variable unitary cost, and S is the sharing and is the percentage of each volume in the company's total production.

The internal rate of return on investment (IRR) is obtained by Equation (17). The higher the RRI over the minimum attractiveness rate (*i*), the more profitable the project [2,9,24].

$$\sum_{n=1}^{N} \frac{CF_n}{(1+IRR)^n} - I = 0 \quad (17)$$

where *CF* is the cash flow, and *I* is the investment or amount invested in the project.

The profit at the end of the project can be calculated using the rates (*i*) and period (*n*) of its financing, using the net present value (NPV), as shown by Equation (18). The higher the NPV, the more profitable the project.

$$\mathrm{NPV} = \sum_{n=1}^{N} \frac{CF_n}{(1+i)^n} - I \quad (18)$$

As the production in the simulated plants is much lower than the total consumption of hydrogen in Brazil, many dependent variables are considered null or constant, reducing the uncertainties in the analyses. Therefore, the capacity and production volume, the minimum rate of attractiveness and the profit margin of the company were varied. As a competitive strategy, the sale price of the H_2 was varied close to the price practiced in Brazil and shown in Table 2. The amount of hydrogen produced in Brazil is close to 400,000 t/year, and maximum variation in the plant's production capacity will be 1,557,528 t/year. This is equivalent to less than 0.4% of the total production and, therefore, it is believed that all products can be absorbed by the market.

Table 2. Variation in the sale price of hydrogen with energy sources [25].

Method		**Cost (USD/kg H_2)**
Fossil fuel (SRNG, CG)		1.38–2.27
Thermolysis and thermochemical cycles		1.99–14.85
Biomass	Gasification	1.77–2.77
	Fermentation	2.57–6.89
Electrolysis	Grid electrolysis	5.73–8.54
	PV electrolysis	5.78–23.27
	Wind electrolysis	5.27–9.37
	Nuclear electrolysis	3.56–7
	High-temperature electrolysis	2.89–6.03

3. Results and Discussion

3.1. Results of Life Cycle Assessment

A summary of material flow and emissions calculations per unit produced are shown in Tables 3 and 4. It is noted that the production of H_2 and O_2 reduces the use of fossil fuels by almost 21 to 94% and 100% air depletion; however it consumes more water and land (limestone). This demonstrates that AEW is a more sustainable fuel than Brazilian steam reforming of natural gas (SRNG) and air cryogenic (AC) plants, which is a gray H_2, and its sustainability increases with the production volume of the plant. It is noted that the AEW process reduces close to 17 kg of CO_2 for each 1 kg H_2 produced. This corresponds to 585.87 t CO_2 for the year (carbon credit).

There are no warnings about gaseous emissions from cryogenic hospital oxygen production. However, Shourkaei et al. [40] reported in a life cycle analysis of cryogenic O_2 production that 1.7 t of depleted air are emitted for each 1 kg H_2 produced (converted values of kg O_2 for kg H_2). Carbon dioxide is responsible for 7800 g/kg H_2, 425 g of particulate matter and 1196 g sulphor dioxid for 1 kg H_2. Even during patient use, for every 1 kg of hospital oxygen consumed, there is an emission of 1.375 kg of CO_2. This CO_2 emissions is 46% of the total GHG emissions, 99.6% of particulate matter, 99.8% of sulphur dioxide of SRNG/AC processes and depleted air is 100% of total air depletion, ammonia and others (i.e., argon and helium).

Table 3. Summary of economic inflow of SRNG, AC and AEW.

Economic in Flow	SRNG/AG (g/kg H_2)	AEW (g/kg H_2)	Reduction (%)
Coal (in ground)	672.05	528.99	21.29
Iron (Fe, ore)	739.73	23.74	96.79
Iron scrap	11.20	2040.22	−18116
Limestone ($CaCO_3$ in ground)	352.47	44.14	87.48
Natural gas (in ground)	11,779.19	702.55	94.04
Oil (in ground)	7375.47	1271.99	82.75
Water	19,796	15,518.03	21.61
Depleted air	1,712,898.81	0	100

Table 4. Summary of emission of SRNG, AC and AEW.

Average Air Emissions	SRNG/AC * (g/kg H_2)	AEW (g/kg H_2)	Reduction (%)
Benzene	0.27	0	100
Carbon dioxide	17,432.83	4273.09	75.48
Carbon monoxide	1.26	0.26	78.06
Methane	334.20	70.24	78.98
Nitrogen oxides	628.14	0.82	99.86
Nitrous oxide	87.48	0.03	99.96
Non-methane hydrocarbons	5.30	1.08	79.66
Particulates	426.57	3.28	99.23
Sulfur oxides	1199.27	3.02	99.75
Ammonia	2.28	0	100
Others	1.14	0	100
Carbon credit (t CO_2/kg H_2)			16.90

* SRNG = steam reforming of natural gas; AC = air cryogenic process; AEW = alkaline electrolysis of water.

3.2. Economic Evaluation of H_2 Production Project

As average values of electricity and water prices are used, to reduce logistical costs it should be considered that the hydrogen production plant can be installed in any location close to highways and the market that absorbs the product. Thus, the size of the plant must be dimensioned according to the demand of the region where it is installed. The following sequence demonstrates the economic viability for each production capacity of the plant (8.89 and 44.45 kg H_2/h).

Table 5 shows how the balance sheets of each hydrogen production plant project studied in this work were composed. Both were analyzed using the maximum production capacity of each plant, as the demand for H_2 is much higher than the production. The sale price for the hydrogen was USD 2 USD/kg and for the hospital O_2 cylinder unit was USD 5 USD/Nm^3. The sale of hospital O_2 corresponds to 58.32% of the plant's revenue and profit.

Table 5. Summary of cash flow of project simulations.

Capacity (kg H_2/h)	H_2 (kg/Year)	Hosp O_2 (Cyl/Year)	Investment (USD)	Revenue (USD/year)	Total Costs (USD/Year)	Profit (USD)
8.89	77,876.4	43,583.53	673,076.92	373,670.4	249,762.51	123,907.9
17.78	155,752.8	87,167.05	1,250,000	747,340.9	446,915.10	300,425.8
26.67	233,629.2	130,750.6	1,730,769.23	1,121,011	651,602.64	469,408.7
35.56	311,505.6	174,334.1	2,500,000	1,591,752	860,361.09	731,390.8
44.45	389,382.0	217,917.6	3,076,923.08	1,868,352	1,043,496.75	824,855.4

OBS: cyl = cylinder; Hosp = hospital.

Figure 3 shows the breakdown of hydrogen production costs with plant size. As can be seen, the highest values refer to the variable costs, wages and investment. The composition of costs varies with the size of the hydrogen production plant. Thus, variable, rates and investment costs increase, while wages and maintenance costs decrease with the size of the plant.

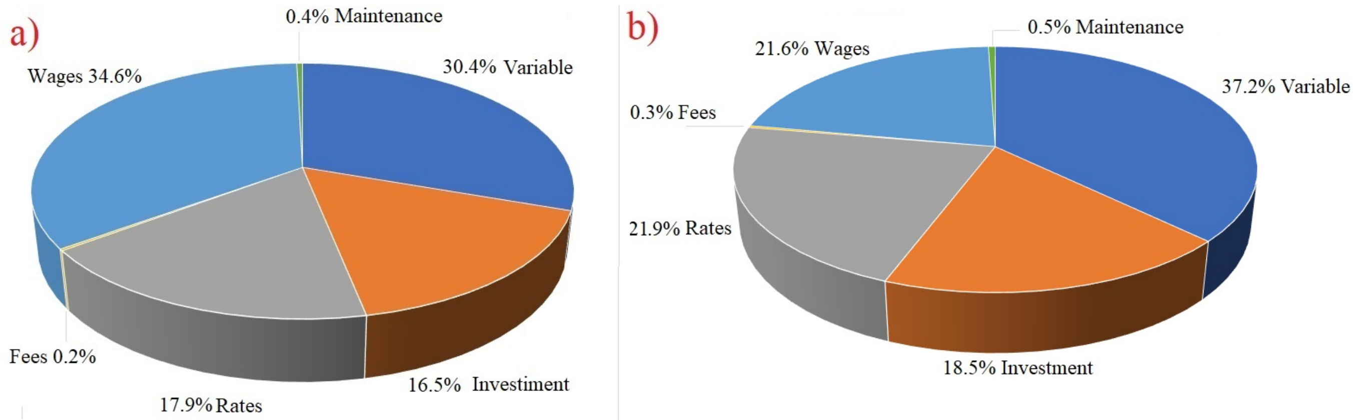

Figure 3. Cost composition of hydrogen production plants. (**a**) one electrolysis kit, (**b**) five electrolysis kit.

Figure 4 shows the variation of the payback and break-even (BP) points on the effect of sale price and different production capacities. The payback was between 2 and 4 years after the sale price of 2 USD/kg H_2. The break-even point varied with the company's production capacity, getting close to 60% of the production volume after commodity prices of 2 USD/kg, only with the sale price. The figure shows that production capacity is not enough to sustain the company economically when sale prices are below 1 USD/kg H_2.

It is noticed that there are not many variations of the curves in Figure 3 because above 2 USD/kg, hydrogen does not have much influence on the production plant revenues, as already noted by Maggio et al. [41] and Ngoah et al. [42]. However, this H_2 production plant project is stable and sustainable, as the hospital oxygen price used in the calculations is 10% of the lowest value sold in Brazil. However, if there is no commercialization of the hospital oxygen, the project is unfeasible.

Figure 5 shows that IRR and ROI vary with sale price for different production scales. There is an increase in the IRR and ROI with the sale price. However, there is a great risk to the project at values of 1 USD/kg H_2, as the rate of return on the investment is between 5 and 10%, which is close to Brazilian inflation (it fluctuated between 5 and 10% between 2020 and 2022) [34]. In these situations, the project would be economically unfeasible.

Thus, at 2 USD/kg, the best economic condition for H_2 is found, because use of capacity volume was less than 60%, the payback is between 3 and 4 years, the IRR is between 25% and 45% and the ROI is between 250% and 588%.

Ji and Wang [31] mentioned that the values found in the literature are between 5.73 and 8.54 USD/hg H_2, when using electricity from the power grid. This demonstrates that the production of H_2 using electricity from the Brazilian energy grid is viable and that the viability has increased with the increased production capacity of the H_2 plant.

By combining the sale of oxygen with that of hydrogen produced by electrolysis using photovoltaic energy, Maggio et al. [41] and Ngoah et al. [42] achieved competitive sale prices between 3.17 and 4.23 USD/kg H_2.

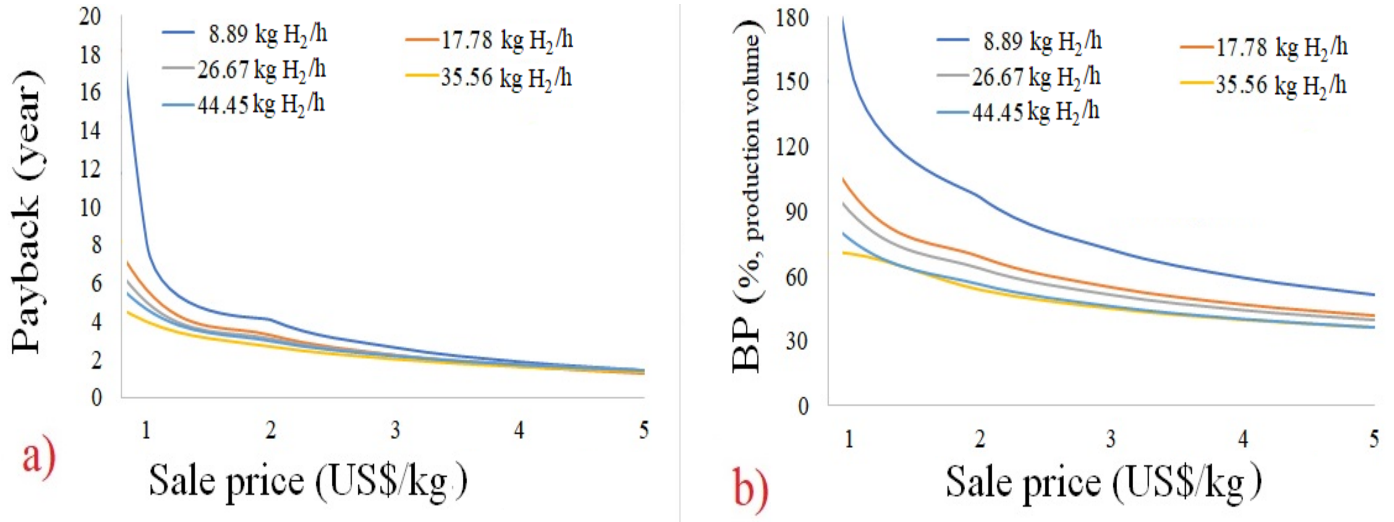

Figure 4. Effect of H_2 sale price on the: (**a**) payback and (**b**) break-even point for different production capacities.

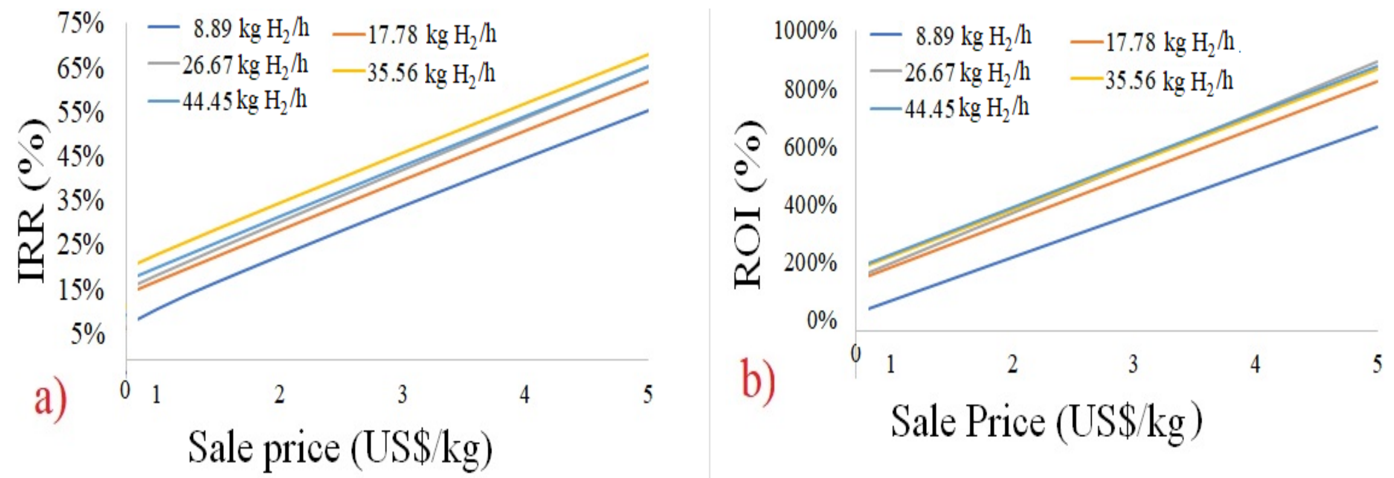

Figure 5. Effect of H_2 sale price on the (**a**) IRR and (**b**) ROI for different production scales.

An analysis of the project's sensitivity to changes in rates, such as the minimum rate of attractiveness (MRA), is showed in Figure 6. As can be seen, the NPV decreases significantly with the increase of the RMA, and projects are not viable at RMA between 20 and 40%, according to its capacities. Larger production capacities overlap and have higher RMA (greater than 40% p.a.), indicating that they have more secure financial conditions. The smaller production capacity, although economically viable, puts the company's situation at risk in countries such as Brazil, where inflation fluctuates up to 10% p.a.

Figure 7 shows the influence of the production volume on NPV, at 2 USD/kg H_2 and 5 USD/Nm^3 hospital O_2. It is observed that plants with a production of 35.56 kg H_2/h and 44.45 kg H_2/h are the ones that most resist changes in production volume; both simulations converged to a reduction in volume of 60%. Plants with a production of 17.78 kg H_2/h and 26.67 kg H_2/h remain economically viable until a 55% reduction in their production volume; however, the plant with only 8.89 kg H_2/h does not resist a 40% reduction in its production volume, indicating that they are the ones with the greatest financial risks.

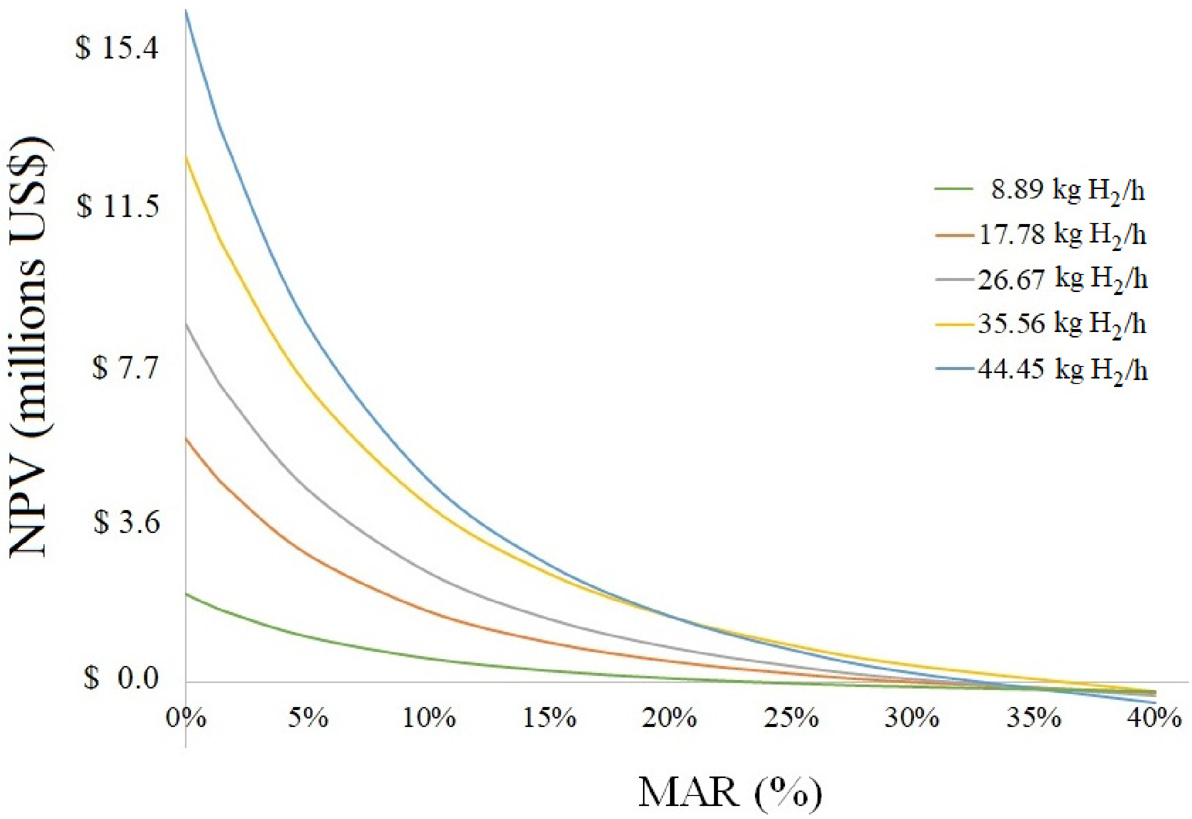

Figure 6. Sensitivity analysis of NVP with minimum rate of attractiveness (MRA) at 2 USD/kg H_2 and 5 USD/Nm3 hospital O_2.

A joint analysis of cost and revenue is shown in Figure 8. This figure shows a product demand curve analogous to perfect competition and a non-linearly proportional variable cost. As can be seen, the curve of marginal costs and unit cost are found in the plant's production capacity equivalent to four electrolytic kits, demonstrating that the greatest economic efficiency of this investment project is found at a production of 44 kg H_2/h (or four electrolysis kits). Mallapragada et al. [43] also identified that costs reduce with the size of the hydrogen production plant.

Table 6 shows the summary of sensitivity analysis of production capacity at 2 USD/kg H_2 and 5 USD/Nm^3 hospital O_2, at the end of the 20 year project. Conceptually, the net present value (NPV) is the change in profit at the end of the project's period; the payback is the time for the project to be paid and the break-even point (BP) is the minimum production volume for the company to make a profit. Internal rate of return on investment (IRR) is the maximum rate at which the project makes a profit, and return of investment (ROI) is the percentage profit on the initial investment. Note that with only 96% of the production volume (break-even point) the company starts to make a profit for 8.89 kg H_2/h capacity, indicating the high risk of this condition. For the others, the BP indicates greater security for these design conditions. It was found that the best condition for each plant capacity is a payback of less than 3 years, an internal rate of return on investment (IRR) greater than 31%, a break-even point between 53% and 68% of the total production volume, a return on investment above 400% and a net present value between USD 1.7 and 13 million. Briefly, the sensitivity analysis showed that all sizes of hydrogen production plant are economically viable, however the best financial condition was found at 35.56 kg H_2/h, corroborating Figure 6.

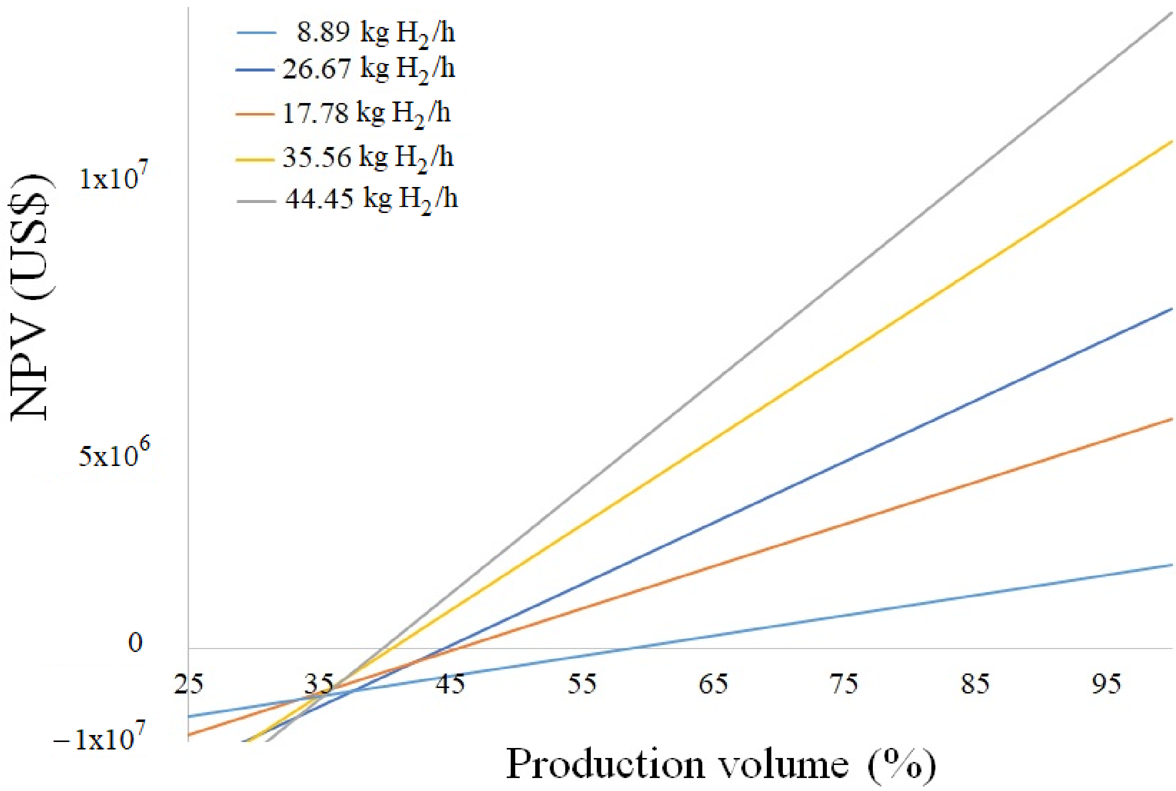

Figure 7. NPV variation with production volume at 2 USD/kg H_2 and 5 USD/Nm^3 O_2.

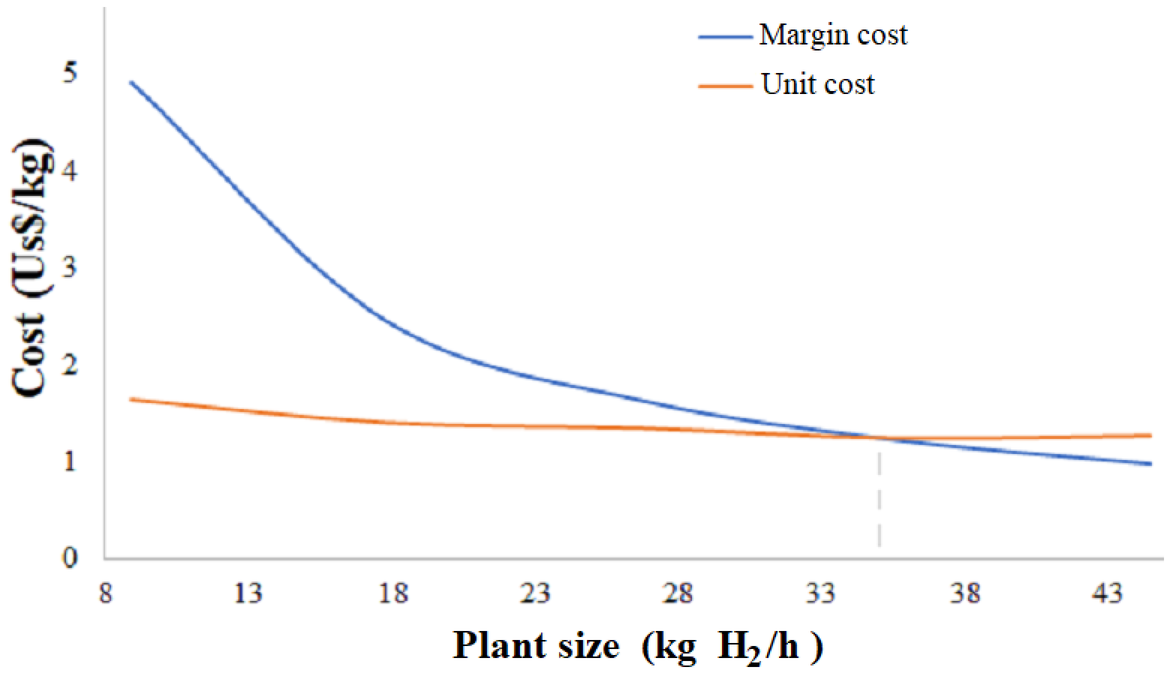

Figure 8. Joint analysis of cost and revenue of hydrogen production project.

Table 6. Sensitivity analysis of production capacity at 2 USD/kg H_2 and 5 USD/Nm^3 O_2.

kg H_2/h	NPV (USD)	IRR (%)	Payback (Years)	PB (%)	ROI (%)
8.89	1.707.214.89	23.7	4.05	96.48	254
17.78	5.227.058.85	29.4	3.25	68.80	378
26.67	8.165.703.93	31.2	3.09	63.28	404
35.56	10.429.465.77	35.7	2.65	53.53	417
44.45	14.329.985.74	32.4	2.93	56.46	425

OBS: NPV = net present value, IRR = internal rate of return on investment, BP = break-even point and ROI = return of investment.

3.3. Leveled Cost Analyses

Table 7 presents the results of the levelized costs of hydrogen for each production plant capacity. When comparing the unit costs with the values in Table 2, it is noted that the cost of producing hydrogen is as low as that of hydrogen produced by the steam reforming of natural gas (SRNG) and four times smaller than those obtained from the energy grid of other countries [25]. As can be seen, all levelized values of the cost of hydrogen in the table decreased with the increase in the production capacity of the hydrogen plant. In addition, they were the lowest price of energy sold in Brazil [14,15] and much smaller than those shown in other scientific research [38], demonstrating the production of hydrogen via alkaline electrolysis using energy from the Brazilian grid is economically and environmentally viable [44].

Table 7. Results of levelized cost of hydrogen (LCOH).

kg H_2/h	Unit Cost (USD/kg H_2)	Levelized Cost (USD/MWh)	Carbon Credit (t CO_2)
8.89	1.64	48.71	26,328.20
17.78	1.40	41.69	52,656.41
26.67	1.34	40.01	78,984.61
35.56	1.24	37.05	105,312.80
44.45	1.27	37.76	131,641

Yates et al. [45] estimated a LCOH of USD 2.70/kg (75 USD/MWh) and used a Monte Carlo approach to explore a wide range of input assumptions, identifying key cost drivers, targets and the localized conditions necessary for competitive stand-alone dedicated PV powered hydrogen electrolysis. Mallapragada et al. [43] studied H_2 production costs spanning the continental United States and through extensive sensitivity analysis, explored system configurations that had achieved USD 2.50/kg (69 USD/MWh) levelized costs.

Avargani et al. [20] reports that there is currently no LCOH of green hydrogen below 70 USD/MWh. Viktorsson et al. [38] reported a LCOH of 300 USD/MWh for hydrogen electrolysis using wind power. Ji and Wang [25] reported a LCOH between 80 and 260 USD/MWh for all renewable energy sources and between 71 and 191 USD/MWh for energy grids. Thus, this work presents better results than those presented in the current literature and shows how to improve IRENA [46] (USD 2.50/kg) forecasts to reach competitive value in 2030.

Figure 9 shows the percentage composition of GHG emissions for the Brazilian energy grid, according to the life cycle assessment. Although the Brazilian energy grid uses more than 80% of sustainable energy sources, it also uses fossil sources (natural gas and coke) and this characterizes the hydrogen obtained from the Brazilian grid as a yellow hydrogen. As noted, more than 80% of GHG emissions (3552 g/kg H_2) are from non-renewable sources used in Brazilian thermoelectric plants. Although it is considered one of the cleanest energy grids in the world, it is essential that the use of these sources be reduced to reduce emissions from the Brazilian grid.

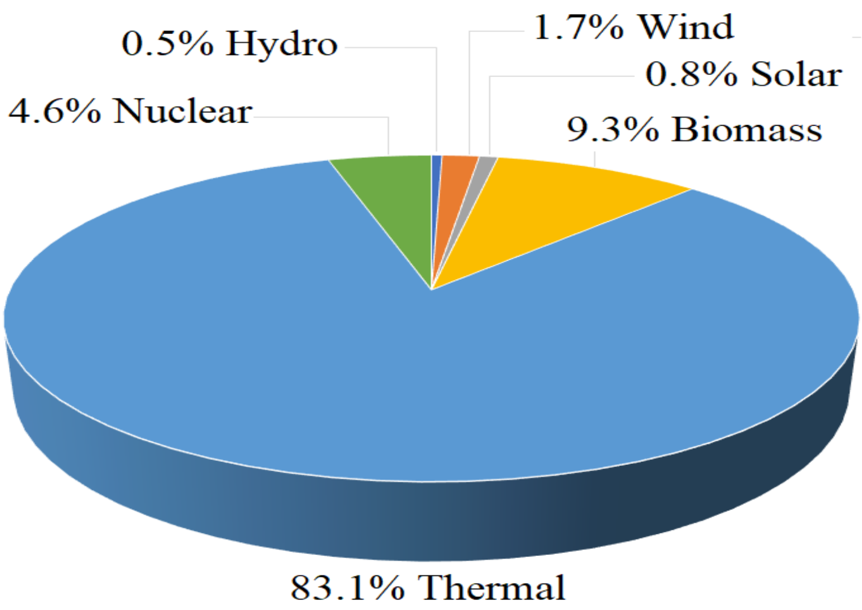

Figure 9. Composition of greenhouse gas emissions of the Brazilian energy grid.

This makes the Brazilian energy grid emit 4.27 kg of CO_2 for every 1 kg of hydrogen, which is similar to the emissions of hydrogen obtained by photovoltaic solar energy. Solar PV-based hydrogen plant generated GHG values between 3.787 and 48 kg CO_2 eq/kg H_2 obtained by Kolb et al. [47], of 5.280 kg CO_2 eq/kg H_2 found for Ozawa et al. [48] and of 5.100 kg CO_2 eq/kg H_2 obtained by Al-Breiki and Bicer [49].

These results are also similar to the application of wind farms in hydrogen production, as the results presented by Ozawa et al. [48] (1.2 kg CO_2 eq/kgH_2) and Al-Breiki and Bicer [50] (3.6 kg CO_2 eq/kg H_2). However, most reports point to a range between 0.68 and 1.78 kg CO_2 eq/kg H_2 for domestic production of wind-based hydrogen [47,51,52].

In addition, from 2019 to 2021 (the COVID-19 pandemic) the price of hospital oxygen varied between 5 and 16 USD/Nm^3 [39], compromising the supply of this gas which is widely used in health networks. As this gas is a by-product of the production of hydrogen by alkaline electrolysis, this process may contribute to the reduction of prices and the supply of hospital oxygen [41,42].

4. Conclusions

From the data, it was found that from a H_2 sale price of 2 USD/kg, all dimensions of the hydrogen production plant become economically viable. However, the plant that produces 8.89 kg H_2/h has many risks, as it must operate close to its production capacity.

The cost of hydrogen varied between 1.26 and 1.64 USD/kg, proving to be very attractive as its value is as low as gray hydrogen.

It was found that the best condition would be a payback of less than 4 years, an IRR greater than 31, a break-even point between 56 and 68% of the total production volume, a return on investment above 400% and a net present value between USD 1.7 and 13 million.

The sensitivity analysis showed that all sizes of hydrogen production plant are economically viable, but the best financial condition was found at 35.56 kg H_2/h, which generated a net present value USD 10.4 million.

In the environmental field, the life cycle analysis showed that the hydrogen production project mitigated from 26 to 131 thousand tons of CO_2, the cost of hydrogen varied between 1.26 and 1.64 USD/kg and a leveled cost of 37.76 to 48.71 USD/MWh., under the conditions studied. This demonstrates that the production of hydrogen via alkaline electrolysis is economically and environmentally viable.

This project is stable and sustainable, as the hospital oxygen price used in the calculations is 10% of the lowest value sold in Brazil. However, if there is no commercialization of the hospital oxygen, the project is unfeasible. The hydrogen production plant must not be installed far from the energy collection network and consumers. In addition, the increase in the price of electricity from the grid can lead to the unfeasibility of the project.

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