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ORIGINAL ARTICLE

Comprehensive case study on the technical feasibility of Green hydrogen production from photovoltaic and battery energy storage systems

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Abstract

The growing demand for alternative energy sources to alleviate environmental impacts highlights the need to move from fossil fuels to renewable energy. This study demonstrated the technical feasibility of using a solar photovoltaic (PV) system for the production of green hydrogen. This research examined electrical and power data from a PV plant in Irecê, Bahia, using open data sources to provide insights into the production of green hydrogen from renewable sources. The system mainly depends on the use of a renewable source, PV solar energy, integrated with batteries, electrolyzers, and hydrogen tanks. Electrolyzer, battery, and hydrogen tank sizing analysis for optimal hydrogen production was effectively conducted using HOMER Energy software. The predicted system topology prioritizes a local DC network, optimizing efficiency for electrolyzers that have inherently low efficiency. The electrolyzer simulation involves initial Python-based sizing and comprehensive sizing with HOMER Energy software, ensuring accuracy within a 10% discrepancy limit. This highlights the importance of analytical calculations and optimization software for sizing more complex systems.

KEYWORDS

battery system, green hydrogen, open data, photovoltaic energy, semi-arid climate

Mohamed A. Mohamed and Adrian Ilinca contributed equally to this study.

1 | INTRODUCTION

In the contemporary context marked by energy crises and the urgent need to tackle global warming, taking advantage of renewable sources as clean fuel has become imperative to promote a sustainable global economy. Meeting this demand involves exploring alternative sources such as wind, solar, hydroelectric, and geothermal energy, offering viable substitutes for conventional fossil fuels. Research consistently highlights the importance of hydrogen as a fundamental element in carbon-free energy production.[1,2] Green hydrogen (GH_2) is particularly recognized as a crucial raw material in mitigating carbon dioxide emissions due to its high energy potential. Given Brazil's predominantly renewable electrical matrix, the country is prepared to position itself as a global leader in this competitive market. Green hydrogen production in Brazil stands to gain from the abundant and versatile renewable resources available, presenting an economic and flexible advantage compared to several other regions around the world. According to the National Energy Plan 2050 (PNE), green hydrogen is a disruptive technology of significant interest for decarbonization, highlighting strategic initiatives to plan the start of production and has shown growing global demand, as seen in Figure 1.[3]

Hydrogen is a potential medium for future energy storage to complement various renewable energy sources. It is obtained through various technological routes, with water electrolysis being a currently widely explored methodology. Since its discovery at the beginning of the 19th century, the production of hydrogen via electrolysis has enabled this product to be obtained from a renewable source as a clean and sustainable product, called green hydrogen.[2,4] This panorama has attracted several players in 2022, where they analyzed a new hydrogen production capacity in the world, with around 22.6 million tons, of which 87% corresponds to green hydrogen. This production capacity was inserted into the world's project pipeline, and it is estimated that for a net-zero scenario, it will be necessary to produce around 300 million metric tons of hydrogen in the world.[5] The water electrolysis process is understood as the separation of water and oxygen. This separation occurs when there is an attraction between the electrodes of ions with opposite charges toward themselves.[5,6] Recognized as a promising and pivotal source of carbon-free energy production, hydrogen holds the potential to address the requirements of diverse sectors, including transportation, residential, industrial, and energy management. Consequently, assessing production costs becomes imperative as a means to mitigate expenses, acknowledging that both production costs and the cost of the electrolyzer are influential factors impacting the

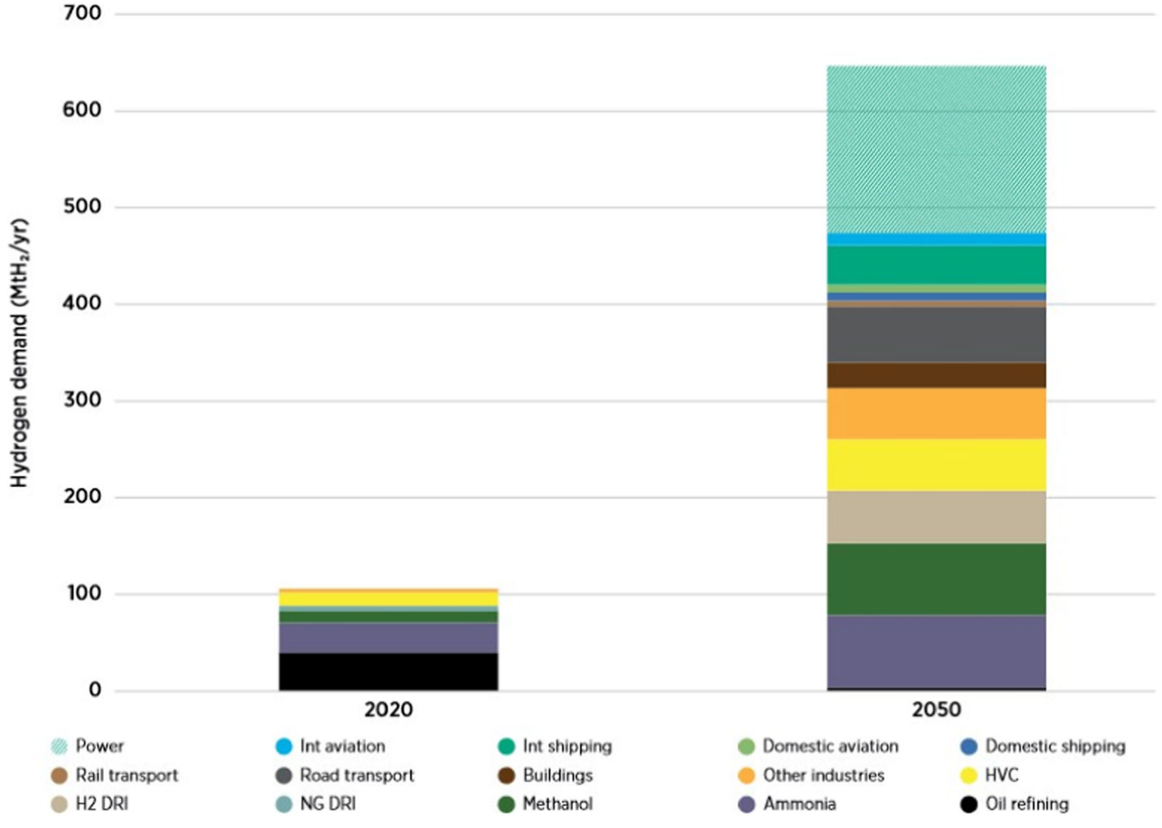

FIGURE 1 Hydrogen demand by application in the years 2020 and 2050.[3]

overall feasibility and viability of hydrogen production.[4] Two crucial factors exerting a substantial influence on the cost of hydrogen production are the energy cost and the cost of the electrolyzer. According to researchers in the field, the energy cost constitutes more than 50% of hydrogen production expenses. To achieve the goal of reaching $2 USD/kg of hydrogen molecule, a pivotal milestone, there must be a requisite 50% reduction in energy costs. Additionally, for hydrogen production through electrolysis to become financially viable, a substantial reduction of approximately 75% in the cost of the electrolyzer is deemed essential. These reductions in both energy and electrolyzer costs are pivotal for advancing the economic feasibility of hydrogen production.[5]

Key sectors for harnessing renewable-based hydrogen include industry, buildings, energy, and transport. In industry, it could replace raw materials such as fossil fuels. In buildings and energy, it can be blended with natural gas; in transport, it can offer low-carbon flexibility through fuel-cell electric vehicles. In this context, electrolyzers, which split hydrogen from oxygen, can make these energy systems even more flexible, helping to incorporate high shares of diverse renewable energies.[7]

Building on the aforementioned considerations, green hydrogen has emerged as a fundamental player in the ongoing energy transition. Its versatility in diverse applications proves instrumental, particularly in addressing segments deemed more challenging in the pursuit of electrification and pollution reduction. The multifaceted nature of green hydrogen positions it as a key component in advancing sustainable solutions across various sectors, contributing significantly to the broader goals of the energy transition.[8]

1.1 | Opportunities of green hydrogen in Brazil

Brazil is emerging as a prominent player on the global stage in the promising green hydrogen market. This clean and renewable form of energy is proving to be pivotal for the future of the global energy matrix. Although the green hydrogen production process still involves high costs compared to fossil energy sources, Brazil is well-positioned to overcome these challenges. According to the 2022 report by the Hydrogen Council, Brazil has the potential to achieve some of the lowest production costs globally by 2050, estimated to range between $1.2/kg and $1.8/kg. This projection places Brazil among the top 10% of producers with the most competitive costs and the capacity to meet the increasing global demand for green hydrogen.[9]

This promising outlook is largely rooted in Brazil's vast potential for clean energy generation. Sources such as solar energy, onshore wind energy and offshore wind energy offer competitive costs to power the electrolysis processes that produce green hydrogen. In addition to becoming a major exporter, Brazil is well-positioned to establish strategic partnerships with European nations facing challenges in green hydrogen production. These European countries are emerging as significant consumers of green hydrogen, creating substantial opportunities for Brazil as a reliable supplier. The country can also cater to the growing demand in Asia, further solidifying its presence in the international market.[10]

It is worth noting that Brazil holds a unique advantage in utilizing biomass, especially ethanol-related technologies, in green hydrogen production. This allows the country to capitalize on the domestic market, facilitating the safe transport and storage of hydrogen through ethanol, thereby contributing to a cleaner and more sustainable energy future.

Brazil is already demonstrating initiatives to achieve this prominence, especially regarding projects involving green hydrogen. In early 2023, the country achieved a remarkable milestone by inauguring the first green hydrogen produc- tion plant at the Port of Pecém, a pilot project led by EDP. This initiative completed its first phase, establishing itself as a pioneer not only in Brazil but also throughout Latin America in the production of GH_2 molecules. Additionally, the country witnessed the announcement of other large-scale ventures, underscoring Brazil's commitment to exploring and promoting the potential of green hydrogen. Another notable project in Bahia, announced in 2022, is slated to receive investments totaling $120 million. This endeavor aims to establish a factory with the capacity to produce 10,000 tons of GH_2 annually, along with 60,000 tons of green ammonia. It is important to note that these figures pertain only to the first phase of the Unigel complex, which encompasses three phases, with the final one scheduled for inauguration in 2027.[10,11]

When examining the announced projects, it is evident that the Northeast region of Brazil plays a fundamental role in the potential for generation and export of green hydrogen. We can see on the map of Brazil the great potential for solar energy generation through climatological data global horizontal solar irradiation, as shown in Figure 2. The Brazilian Energy Research Company (EPE) estimates that the region is responsible for 46.85% of hydrogen generation potential. This is due to its strategic location and the presence of large wind and solar farms in the region, presenting the states with the highest production potential in the country: Bahia (BA) with 13.28%, Ceará (CE) with 8.83%, and Rio Grande do Norte (RN) with 6.72%, see Figure 3. Furthermore, the Northeast region already has well-established ports, such as

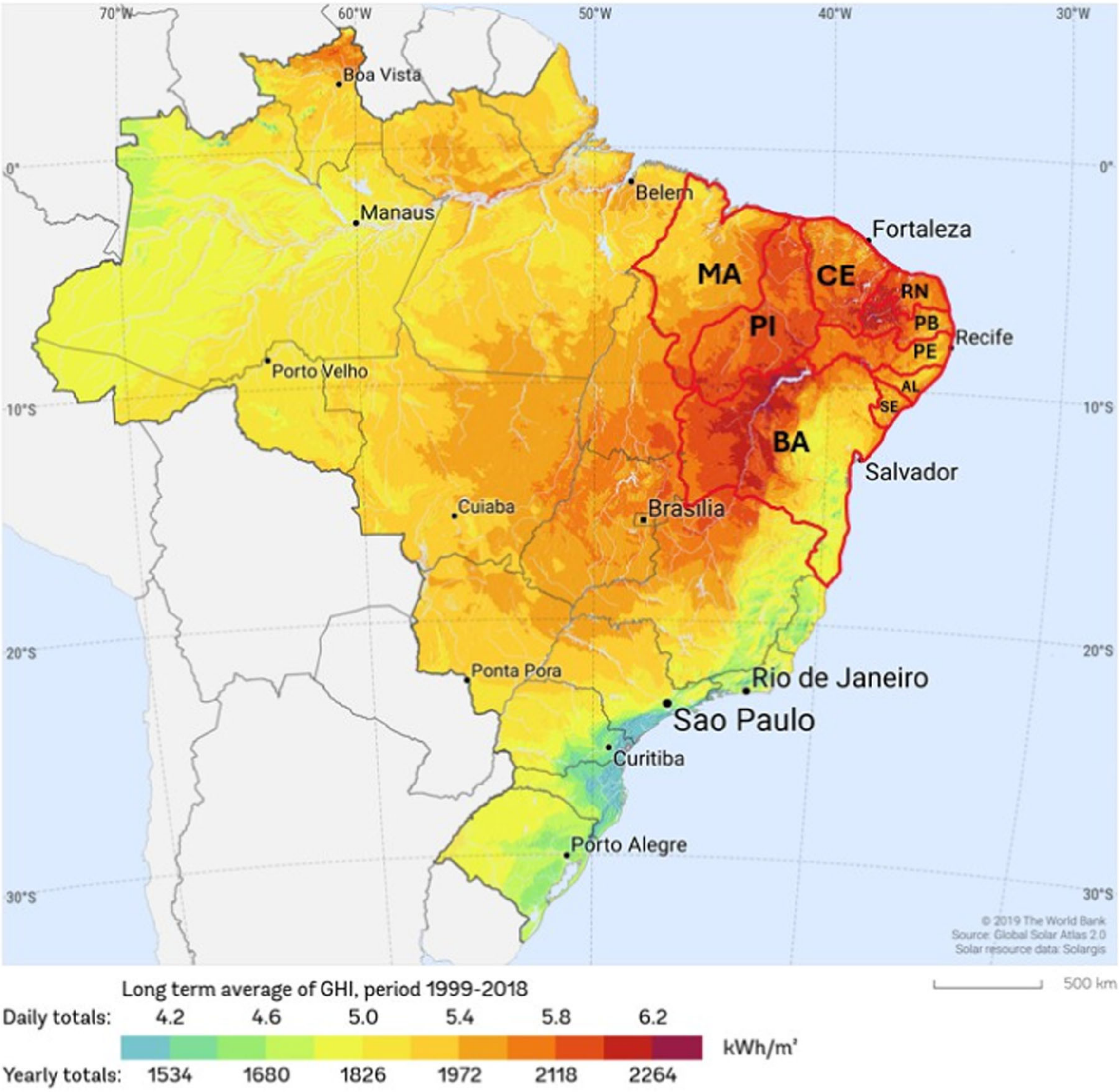

FIGURE 2 Horizontal global solar irradiation. Data collected from reference 12.

Porto do Pecém, which is home to Brazil's first green hydrogen project. These ports have the potential to be adapted for the safe and efficient transport of green hydrogen, in liquid or gaseous form, to national and international destinations.[10,11]

However, it is important to highlight that logistical, infrastructural, and regulatory challenges still need to be overcome for the export of green hydrogen to become a concrete reality in the Northeast region.

1.2 | Objective and contributions

The objective of this article is to conduct a simulation of a green hydrogen production system based on a real photovoltaic (PV) plant located in the region with the highest hydrogen generation potential in Brazil, specifically in the state of Bahia (BA). To achieve this goal, data from a PV plant installed at the Irecê Campus of the Federal Institute of Bahia (IFBA) with a capacity of 46.44 kWp was chosen for use, although it provides information for only 9.36 kWp. Furthermore, the data from this plant are available as open data on the Kaggle platform, facilitating research replicability and transparency.

To achieve this objective, a preliminary basic sizing is performed using analytical calculations through the Python programming language. This initial phase aims to guide the results of the final sizing, which will be executed using the Homer Energy software. This software is widely recognized and used for the optimization of renewable and hybrid energy systems, including hydrogen production systems.

The primary contribution of this article is the in-depth investigation of the technical and economic

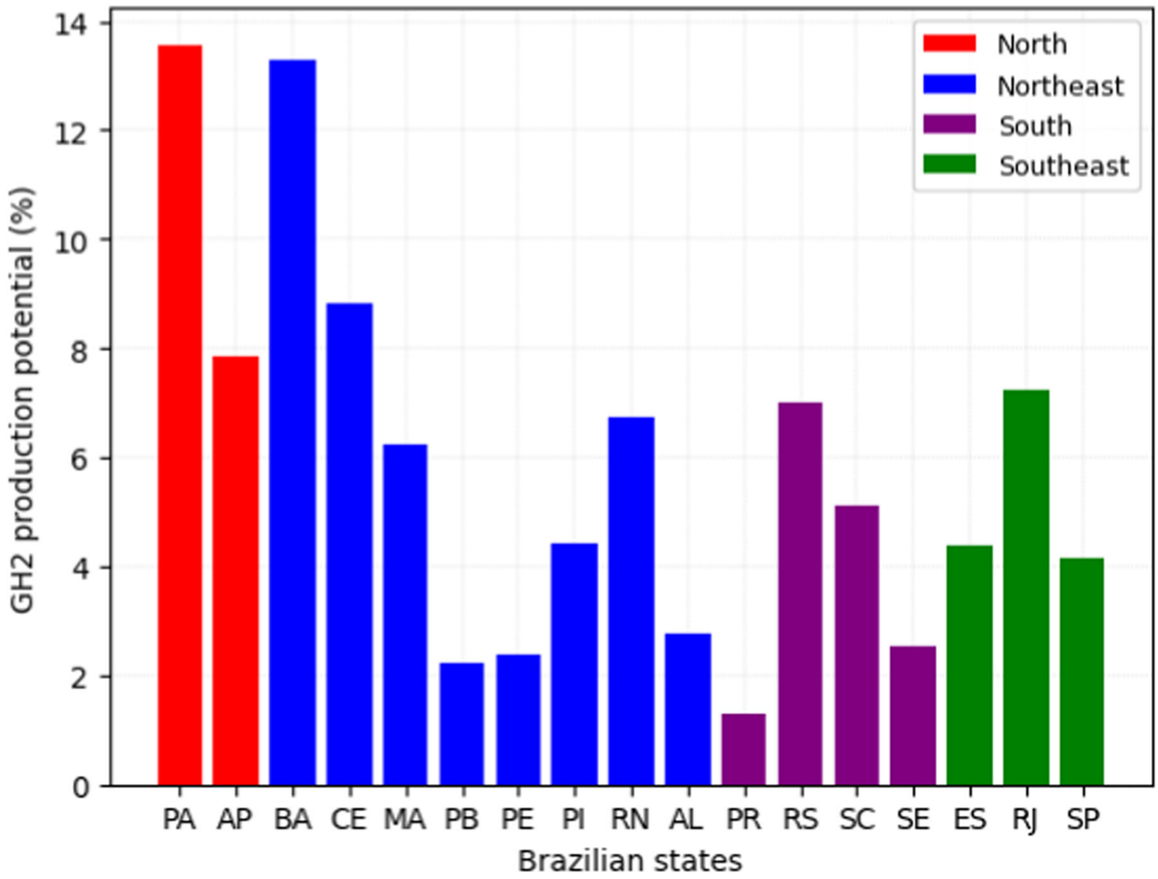

FIGURE 3 GH_2 production potential by region in Brazilian territory. Data collected from reference 11.

feasibility of green hydrogen production from a real PV plant in the Brazilian context, considering a strategically located site with high renewable energy generation potential.

Furthermore, the methodological approach that combines preliminary analyses with the use of specialized software is an important contribution to the field of renewable energy research and hydrogen production. This demonstrates an effective strategy for sizing and assessing the viability of green hydrogen production systems based on renewable energy sources, making the transition to a low-carbon economy more tangible and practical.

The remainder of this article is organized as follows: Section 2 begins by outlining the current state of hydrogen technology, including a quick overview of what hydrogen is, the technological routes for its production, the process of producing hydrogen via water electrolysis, what electrolysis is and the types of electrolyzers most used commercially. The modeling of the proposed system is described in Section 3, together with data and methods. The case study involving the system simulation is developed in Section 4. The results obtained are described in Section 5. Finally, in Section 6, the conclusion is drawn.

2 | THEORETICAL FOUNDATION

Considered a clean energy source, green hydrogen stands out as an energy vector due to its energy capacity compared to other sources.[13] In addition to being an excellent carrier of sustainable energy, it presents some advantages such as high efficiency in the process of generating and storing energy in liquid and gaseous form together with metal hydrides.[1] Due to its storage possibility, green hydrogen allows export, but its application is still limited due to the difficulties in obtaining it.[14] In the literature, there are several processes for its production, including electrolysis and chemical reactions.[15] Therefore, it can enable greater input of renewable energy, such as wind and solar. It can be seen as a resource to promote interconnection between the fuel, electrical and industrial markets, among others.[16] There are several methods of classifying hydrogen according to its production processes, such as water electrolysis, thermochemical hydrogen production, and steam reforming, among others. Given this context, it is possible to obtain hydrogen from various raw materials and natural (geological) occurrences through different technological routes. In this sense, according to the hydrogen production processes, it is classified based on its production route or the energy used. Therefore, analyzing from a technical point of view, the most appropriate term to classify the types of hydrogen is to differentiate in relation to their colors[16]:

1. Brown or black hydrogen: produced from mineral coal without CCUS (carbon capture, use and sequestration);
2. Gray hydrogen: produced from natural gas, without CCUS (carbon capture, use, and sequestration);
3. Blue hydrogen: produced from natural gas with CCUS (carbon capture, use, and sequestration);
4. Turquoise hydrogen: produced from the pyrolysis of natural gas; and
5. Green hydrogen: produced via electrolysis of water with energy from renewable sources.[16]

Recently, the industry has made advances to scale up cells and batteries to increase hydrogen production capacity via water electrolysis.[17] Therefore, the ideal size of the battery of a PV/battery system is essential. The optimal use of these intermittent energy sources, such as solar or wind, depends on the forecast of this energy resource. According to recommendations from the EPE, the time required to measure the solar resource is at least 12 months to estimate the solar energy production of a location.[18] Studies related to PV systems and batteries have been relevant, as battery energy storage systems allow energy to be stored in some way so that it can later be converted into electrical energy and used for its intended purpose, making battery systems essential to maintain grid stability, allowing the electrolyzer to continue fully functioning.[19]

2.1 | Green hydrogen from water electrolysis

The water electrolysis process is an attractive approach to producing hydrogen with low carbon emissions. Hydrogen produced by electrolysis with water is obtained through an electrolyzer that separates water into hydrogen and oxygen. These electrolyzers can contribute to energy systems, as their consumption can be adjusted to accompany the generation of renewable energy, where hydrogen becomes a solution for energy storage. They can also offer grid balancing services (frequency regulation up and down, descending) and, at the same time, operate at optimal capacity to satisfy the hydrogen demand from industry and the transport sector, or for gas injection into the grid.[7,20]

In the literature, we find several studies that focus on the production of green hydrogen through renewable energy. Yates et al.[21] considered hydrogen production only from solar panels that can be installed in remote locations, performing a detailed LCOE calculation for a standard electrolyzer driven by remote PVs. In this operation, it was observed that there is an operational disadvantage due to the limitations of the electrolyzer. However, the advantage is installing large PV systems with considerable loss reduction in connection with the grid. On an industrial scale, hydrogen is considered and presented as a mature and cost-competitive technology in 2030.[22]

In this context, the Fraunhofer Institute for Solar Energy Systems ISE[17] created a bottom-up cost model and carried out a cost study on behalf of the NGO Clean Air Task Force (CATF). A fundamental cost model was developed with two systems of 5 and 100 MW for the electrolysis of alkaline water and PEM to cover the needs of decentralized and centralized applications.[17] The results indicated that the battery is the most expensive component of the system. These battery-specific costs can be practically halved within 10 years for both types of electrolysis cell, from around €200/kWDC to less than €90/kWDC for AEL batteries and from €220/kWDC to around €380/KWDC for PEM batteries. However, stack costs do not just dominate system costs. Instead, its composition consists, in addition to the battery, of other components such as gas and water treatment, refrigeration systems, and power electronics, exemplified in Figure 4.[17]

In studies carried out on a university campus,[23] a technical and economic analysis was carried out at hydrogen filling stations that are supplied with hydrogen produced locally through PV solar energy and also evaluated the levelized cost of energy (COE) from the excess production of PV solar energy.[24] For the proposal, different volumes of vehicles in the fleet were considered, with hydrogen demand ranging from 20 to 185 kg. This plant is based on hydrogen storage, compression, a pre-cooling unit, and an electrolyzer. This hydrogen production plant was developed using PV solar energy.[25] As a result, it was observed that the costs of producing green hydrogen and the coverage rate of its annual production are influenced by the size of the PV system, the capacity of the electrolyzer and the storage capacity of the hydrogen tank.

As countries promote deep decarbonization strategies, green hydrogen produced from renewable sources via water electrolysis is expected to be at the center of the energy transition as a fundamental piece of the clean energy process. Therefore, the global energy system needs to undergo profound changes to achieve the goals of the Paris Agreement. Consequently, hydrogen could be the ideal connection for the energy transition, as the

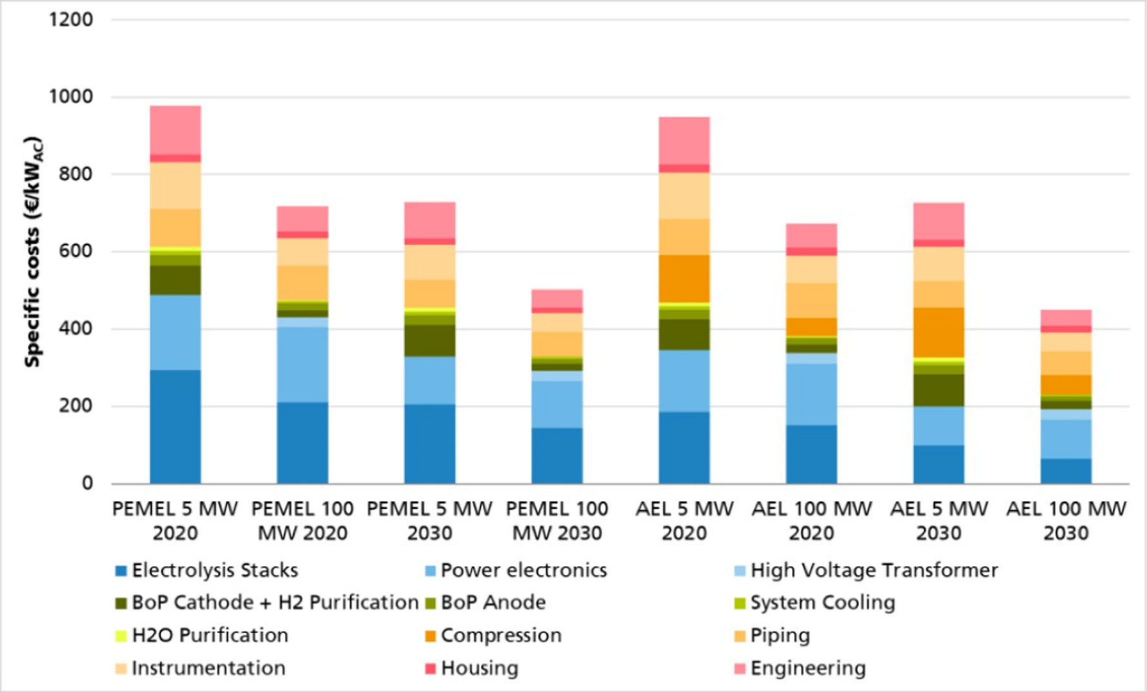

FIGURE 4 Alkaline and PEM electrolysis system cost for different system capacities in 2020 and 2030. PEM, proton exchange membrane.[17]

hydrogen produced, in turn, can provide clean energy for other sectors of society, such as industry, transport, and buildings.[7] However, more incentives and government support are needed, as despite the reduction in the cost of renewable energy, hydrogen production from renewable energy alone may not be competitive in terms of costs and the combination of renewable energy and grid connection suggested in a future study to increase capacity utilization.[26]

2.1.1 | Electrolyzer technologies

The market for electrolyzers for green hydrogen production is still on the rise. In this way, this concept of green hydrogen essentially involves its production using renewable electricity, that is, from renewable sources. The main way to produce electrical energy following this trend is to use solar and wind technology, both with extreme potential in any future scenario.[27] The low price of electricity is essential to make green hydrogen competitive in the market. This means that even with cost reductions in electrolyzers, cheaper electricity is needed. In practice, this means a cost of less than 1 USD/kg before 2040 and the cost of the electrolyzer and electricity is expected to decrease over the years.[27] The cost per kilogram of hydrogen produced by electrolysis depends on the use of electrolyzers. A recent study analyzed the correlation between the production of electrical energy generated from hydrogen in the electrolysis process and the electrolyzer utilization factor.[4] The Department of Energy's (DOE) Hydrogen, Fuel Cell, and Infrastructure Technologies Program aims to develop technologies aimed at the efficient, low-cost production of hydrogen through electrolysis. This study was based at the National Renewable Energy Laboratory (NREL) for this technical assessment. This development leads to several solutions that will provide low-cost and successful results in the short, medium, and long term.[28]

In the technical analysis, it was possible to evaluate the costs of hydrogen production from the electrolytic process and verify that these processes largely depend on the cost of electrical energy, system efficiency, and capital costs. The results showed that if supply systems can use electricity at commercial prices compared to electricity at industrial prices (4.83¢ vs. 7.89¢ per kWh) and hydrogen prices can be reduced by 31%, resulting in an increase in system efficiency limited to 78%. Therefore, it can be seen that increasing efficiency will not reduce costs as much as a significant reduction in the price of electricity.[28]

Currently, four main electrolyzer technologies are most commonly used or are being developed: alkaline (ALK), proton exchange membrane (PEM), anion exchange membrane (AEM) electrolyzers, and solid oxide electrolyzers (SOEC).[7,29]

Due to their great flexibility, PEM electrolyzers have achieved great market traction. They are commercially available, while ALK electrolyzers have been used by industry for almost a century and are well developed, but for nonenergy purposes, particularly in the chemical industry, to manufacture chlorine.[29] There are also SOEC and AEM electrolyzers that have high development potential and high potential to improve energy efficiency. However, they are in the development phase and, unlike ALK and PEM, they work at high temperatures.[29] PEM and ALK electrolyzers are often operated at temperatures of (600°C).[30]

The DOE Hydrogen and Fuel Cell Program Registry[31] provided a technical analysis regarding the costs incurred in producing hydrogen from PEM electrolyzers. This analysis identified that hydrogen can be viably produced at a cost of between 4 and 6 USD/kg-H2 currently from renewable and grid raw materials. Yaici et al.[32] investigated the feasibility of using an HRES with hydrogen and battery storage alternatives to meet the energy needs of a stand-alone home in Canada. In this study, the HOMER Energy software was used to build models with two different configurations of the microgrid system (distributed energy system in which energy generation is close to the loads). The first system consisted of PV solar panels, diesel generators, hydrogen production and storage (PV-hydrogen-diesel) and the second with battery storage (PV-battery-diesel). The results showed that (PV-battery-diesel) is about 60% more economical than PV-hydrogen-diesel), with a total net cost of $394,724 and a COE of $0.56/kWh. This is because hydrogen technology is relatively new, while batteries are already established in the market. Considering the relevance of green hydrogen for contemporary society and future generations, as well as the process by which green hydrogen is generated, it is necessary to understand and invest in the electrolyzer market to assess the viability and costs involved in this production. In the future, the costs associated with hydrogen storage are likely to decrease. At that point, it may be more favorable to utilize hydrogen due to its zero carbon emissions and high energy density.

3 | SYSTEM MODELING

This section presents the methodology with a description of the software used in the simulations. Based on the literature, it was possible to identify different types of software that simulate the behavior of equipment that constitutes a hybrid system, microgrid, or minigrid. Once the input data has been entered, such as system load, PV system power, electrolyzer power, battery, and storage system, HOMER loads all the necessary information into the system to start the simulations. During the simulation, HOMER compares all possible configurations in relation to the components and shows the best configurations as a result.

3.1 | System modeling using HOMER Energy Software

This topic focuses on the mathematical modeling techniques employed by the HOMER Energy software. It covers the simulation of various components essential in renewable energy systems, including PV systems, green hydrogen production, hydrogen storage tanks, and battery energy storage. Each model is crucial in assessing the feasibility, efficiency, and economic viability of renewable energy projects.[33]

3.1.1 | HOMER energy simulation

The HOMER Energy software was used to conduct a comprehensive system sizing. Inputs included weather data (solar irradiance, wind speeds), load profiles, and component specifications. The software simulated various microgrid configurations, determining the optimal size for each component by minimizing the Net Present Cost (NPC) while adhering to system demands.

3.1.2 | Python simulation

The Python script utilized real-time performance data from a 46.44 kWp PV system at the IFBA Irecê Campus. The script accounted for system power, efficiencies of the PV system and electrolyzer, average primary load, and auxiliary consumption of the electrolysis configuration. The output included detailed sizing of the electrolyzer, battery, and hydrogen storage requirements.

3.1.3 | Data set description

The data set available on Kaggle includes real-time performance data from the 46.44 kWp PV system installed at the IFBA Irecê Campus. The generation of this PV plant is distributed with five different PV mod- ule technologies. For this analysis, the arrangement with Cadmium Telluride technology was considered, consisting of 96 modules of 97 Wp and a 10 kW inverter. This section details the contents of the datasets, including power, efficiency, and operating parameters. Data is presented at intervals every 15 min.

3.1.4 | PV system

PV systems convert sunlight into electricity and are pivotal in harnessing solar energy. The HOMER software models a PV system based on several factors[33]:

1. Rated capacity (Y_{PV}): The power output of the PV array under standard test conditions, measured in kW.
2. PV derating factor (f_{PV}): A percentage factor that accounts for real-world conditions affecting the PV system efficiency.
3. Incident solar radiation (G_T): The solar radiation incident on the PV array in the current time step, measured in kW/m^2.
4. Standard test conditions for radiation ($G_{T,STC}$): The incident radiation at standard test conditions, typically taken as 1 kW/m^2.
5. Temperature coefficient of power (α_P): A factor representing the change in power output with temperature, measured in % per °C.
6. PV cell temperature (T_c): The temperature of the PV cell in the current time step.
7. Standard test conditions for temperature ($T_{c,STC}$): The PV cell temperature under standard test conditions, typically 25°C.

The formula to calculate the output of the PV array in HOMER, considering temperature effects, is given by:

$$P_{PV} = Y_{PV} \times f_{PV} \times \frac{\bar{G}_T}{\bar{G}_{T,STC}} \times (1 + \propto_P \times (T_c - T_{c,STC})). \quad (1)$$

3.1.5 | Green hydrogen production via electrolysis

Green hydrogen production via electrolysis involves splitting water into hydrogen and oxygen using electrical energy. The efficiency of the electrolyzer plays a crucial role in determining the energy requirement. Key factors in this model include[33]:

1. Quantity of hydrogen (Q_{H2}): The target production volume of hydrogen.
2. Higher heating value of hydrogen (HHV_{H2}): The amount of energy released when hydrogen is combusted.
3. Electrolyzer efficiency (η_{el}): The ratio of the energy input to the chemical energy stored in hydrogen.

The required electrical energy for hydrogen production is given by:

$$E_{el} = \frac{Q_{H2} \times HHV_{H2}}{\eta_{el}}. \quad (2)$$

This formula helps in determining the electrical input needed for a specified hydrogen output.

3.1.6 | Hydrogen storage tank

Hydrogen storage is critical for managing the supply and demand of hydrogen fuel. The modeling of a hydrogen storage tank involves several considerations[33]:

1. Tank capacity: Determines how much hydrogen can be stored.
2. Pressure and temperature: Hydrogen storage dynamics are heavily influenced by these factors.
3. Leakage and safety: Includes assessing the risk of hydrogen leakage and implementing safety measures.

HOMER calculates the hydrogen tank's autonomy by considering the energy capacity of the hydrogen tank and the electric load. The formula used for this calculation is as follows:

1. Hydrogen tank capacity (Y_{htank}): The total storage capacity of the hydrogen tank, measured in kilograms of hydrogen.
2. Lower heating value of hydrogen (LHV_{H2}): The energy content of hydrogen, typically taken as 120 MJ/kg.
3. Average primary load ($L_{prim,ave}$): The average primary electric load, measured in kWh/day.

The autonomy of the hydrogen tank, $A_{ht\ ank}$, in hours, is calculated using the equation:

$$A_{htank} = \frac{Y_{htank} \times LHV_{H2}}{L_{prim,ave}}, \quad (3)$$

where A_{htank} is the autonomy of the hydrogen tank in hours; Y_{htank} is the capacity of the hydrogen tank in kilograms; LHV_{H2} is the lower heating value of hydrogen in MJ/kg; and $L_{prim,ave}$ is the average primary load in kWh/day.

This equation provides a measure of how long the stored hydrogen can meet the energy demand, which is essential for sizing and designing hydrogen storage systems in renewable energy projects.

3.1.7 | Energy storage—kinetic battery

Battery storage systems are essential for managing the intermittency of renewable energy sources. The HOMER model for battery storage considers[33,34]:

1. Capacity: The total amount of energy a battery can store.
2. Depth of discharge: To what extent can a battery be used relative to its total capacity.
3. Charge/discharge efficiency: Efficiency with which the battery can be charged and discharged.
4. Degradation: The decrease in battery performance and capacity over time.

The energy balance in the battery is modeled as:

$$E_{\text{stored}} = (E_{\text{initial}} + E_{\text{in}} \times \eta_{\text{charge}} - E_{\text{out}})/\eta_{\text{discharge}}, \quad (4)$$

where E_{in} is the energy entering the battery (charging), E_{out} is the energy leaving the battery (discharging), η_{charge} is the charging efficiency, $\eta_{di\ schar\ ge}$ is the discharging efficiency, $E_{stor\ ed}$ is the energy stored in the battery, and $E_{i\ ni\ ti\ al}$ is the initial energy. This model helps optimize battery usage to achieve maximum efficiency and longevity.

3.2 | Analytical modeling using Python software

The initial simulation using the analytical method executed by the Python software was carried out considering the following input variables:

1. Annual energy production (PVEnergy Annual): annual production of the PV plant (Actual data collected from the plant from Kaggle Database) in kWp. Considered 14,261.87kWp/ano.
2. Energy for hydrogen production (E_{H2kg}): Energy required to produce 1 kg of hydrogen. For the study, 33 kg was needed.
3. Other consumption in the electrolysis system (c_{elect}): Represents other consumption in the final electrolysis process, measured in %. Considered 15%.
4. Electrolyzer efficiency (η_{elect}): represents the amount of energy contained in hydrogen due to the energy consumption of the electrolysis process. In the most modern electrolyzers, efficiency varies from 60% to 90%. In this study, an efficiency of 70% was considered.
5. Average primary (Lprim): Average primary load in kWh/day. Considered 11.57173.

knowing that the annual energy production produced by the PV system in Wp is given by

$$\text{PVEnergy Annual Wp} = \text{PVEnergy Annual} \times 1000. \quad (5)$$

The formula to calculate the energy required for the electrolyzer is given by:

$$E_{\text{H2}} = \text{PVEnergy Annual} \times (1 - \text{c}_{\text{elect}}). \quad (6)$$

Therefore, hydrogen production for this system is given by:

$$m_{\text{H2}} = \frac{E_{\text{H2}}}{E_{\text{H2kg}}}. \quad (7)$$

This way, we can calculate the autonomy of the hydrogen tank in hours:

$$A_{\text{htank}} = \frac{(m_{\text{H2}} \times 120)}{L_{Prim}}. \quad (8)$$

With these data, it is possible to obtain the electrolyzer power as follows:

$$P_{Electrolyzer} = \frac{E_{H2}}{A_{htank}} \times \eta_{elect} \quad (9)$$

4 | CASE STUDY

This section will present the methods for sizing system loads, characterizing the PV system and presenting the simulation environments based on the analytical method (Python) and Homer Energy.

4.1 | Resource local characterization

For the development of this study, technical aspects of data obtained from a PV solar plant located at the Federal Institute of Bahia, Irecê-BA (−11.3264277, −41.8657846) will be evaluated Figure 5. This on-grid solar photovoltaic system is composed of 336 PV modules distributed in five different technologies: polycrystalline silicon (p-Si), cadmium telluride (CdTe), copper, indium and gallium selenide, high and low voltage amorphous silicon (a-Si/c-Si), totaling 46.44 kWp of peak power, five 10 kW solar PV inverters, totaling a nominal AC power of 50 kW and a solarimetric station.[36]

FIGURE 5 IFBA's reference photovoltaic plant linked to the project "Development and testing of systems for photovoltaic solar generation in high-temperature conditions in semi-arid regions of northeastern Brazil."[35]

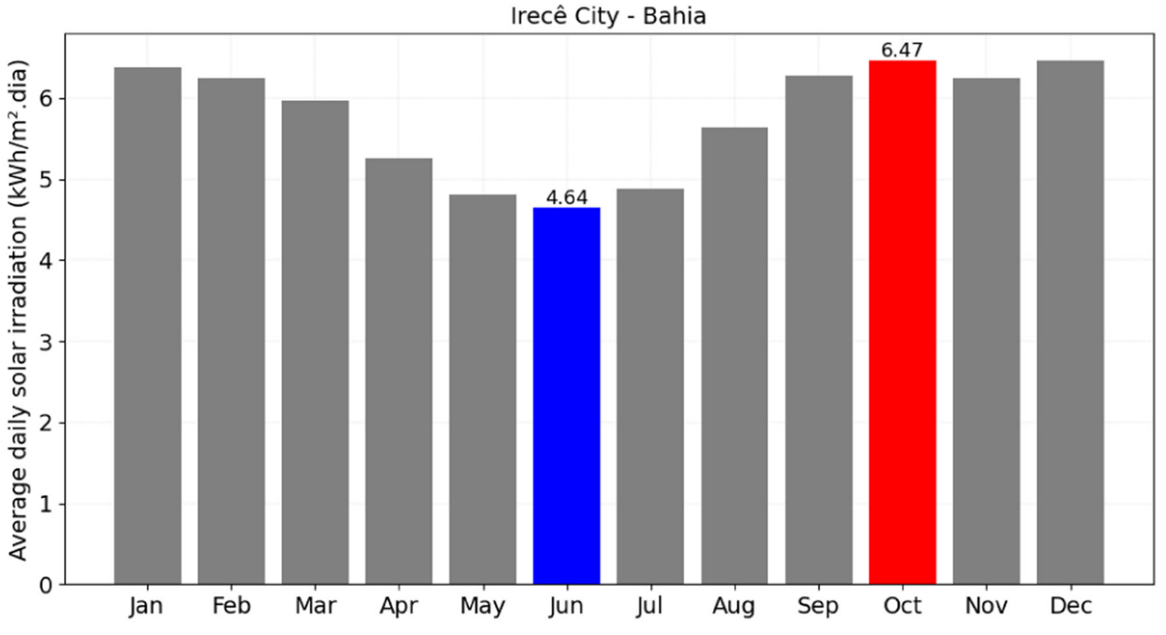

FIGURE 6 Annual solar irradiation trends in Irecê. Data from collected.[37]

The city of Irecê experiences a semi-arid tropical climate characterized by extended periods of clear skies and a low incidence of rainfall. This climatic profile leads to more sunny days and, consequently, to augmented opportunities for solar energy generation. Climatological data indicate that Irecê benefits from global horizontal solar irradiation exceeding 5.5 kWh/m^2 per day. Figure 6 illustrates a trend of high irradiation levels throughout the year, with likely peaks occurring during the dry season when cloud coverage is further reduced. The irradiation peaks are observed from October to February, reaching a maximum of 6.47 kWh/m^2 per day, while the least favorable month is June, with 4.64 kWh/m^2 per day.[37]

4.2 | System topology

The configuration of the system in question to be dimensioned is designed for a local DC network connection of all components (Figure 7). In this system, PV solar energy is the primary source of power. Solar panels convert sunlight into DC electrical energy, which is then used to power the electrolyzer. Thus, the DC connection

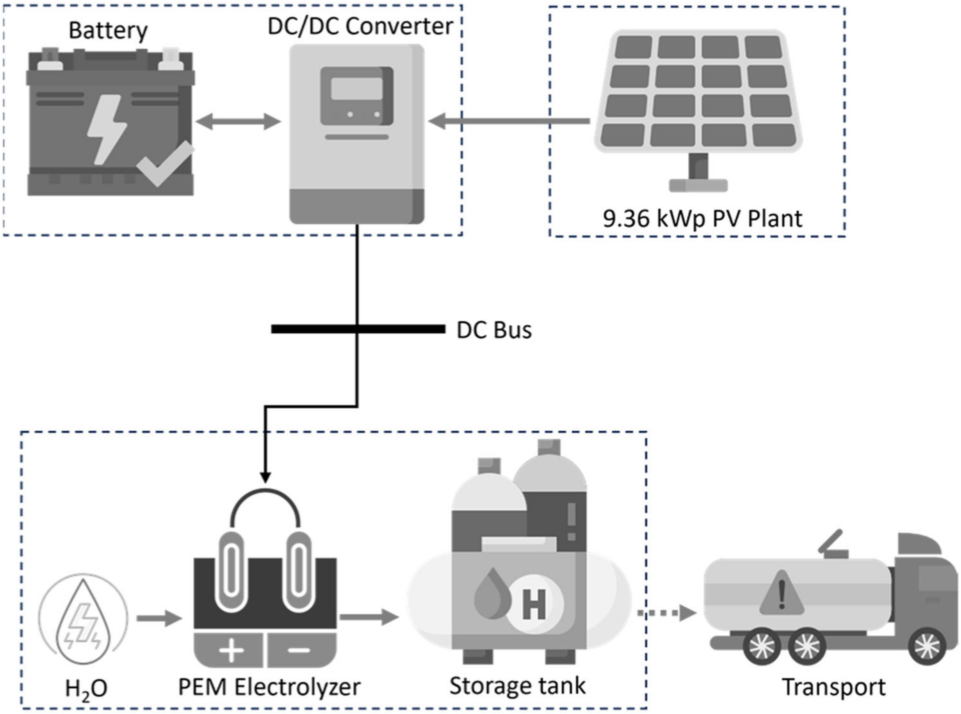

FIGURE 7 GH_2/PV/battery system topology. PEM, proton exchange membrane; PV, photovoltaic.

aims to maintain production efficiency, as electrolyzers can have inherently low efficiency.

4.3 | Electrolyzer simulation process

The simulation process (see Figure 8) begins with the collection of PV data, which is essential for two sizing procedures. Initial sizing uses an analytical method executed in Python, considering several inputs such as the power of the system—reference 36, the real generation of electrical energy from the PV system of the plant installed at the Federal Institute of Bahia, Campus Irecê,[36] the efficiencies of both the PV system and the electrolyzer, the average primary load in kWh/day, the auxiliary consumption of the electrolysis configuration and the energy required to produce 1 kg of hydrogen.

The Homer Energy software conducts a comprehensive system sizing. Known for its extensive application in technical, economic, and environmental feasibility analyses of hybrid power systems worldwide, HOMER processes weather data - solar irradiance and wind speeds - along with load profiles and component specifications. These inputs facilitate the simulation of various microgrid configurations. Subsequently, HOMER determines the optimal size for each component within a configuration, guided by the objective of minimizing the NPC while adhering to the demands of the system, such as the minimum capacity shortage allowed, as defined in reference 32.

A comparative analysis of the electrolyzer power output from both the Python and HOMER Energy simulations is then undertaken. Should this comparison reveal a discrepancy of less than 10%, the process is deemed complete. If not, an error analysis followed by necessary adjustments is performed, ensuring that the system's sizing aligns accurately with performance requirements.

Furthermore, the preservation of energy quality is crucial for the proper operation of the electrolyzer, as voltage fluctuations or interruptions can cause operational issues. Therefore, a battery system is integrated into the setup to operate as a network-forming master and provide energy stability. The DC topology is advantageous for this system because the direct current is more stable and less sensitive to voltage fluctuations compared to AC. This helps to maintain the stability of the electrolyzer operation and prevents unwanted shutdowns.

4.3.1 | Electrolyzer simulation in Python

For simulation in the Python software, some input data were considered (Table 1):

1. Annual production of the PV plant (actual data collected from the plant from Kaggle Database)[36];
2. Efficiency of the PV system;

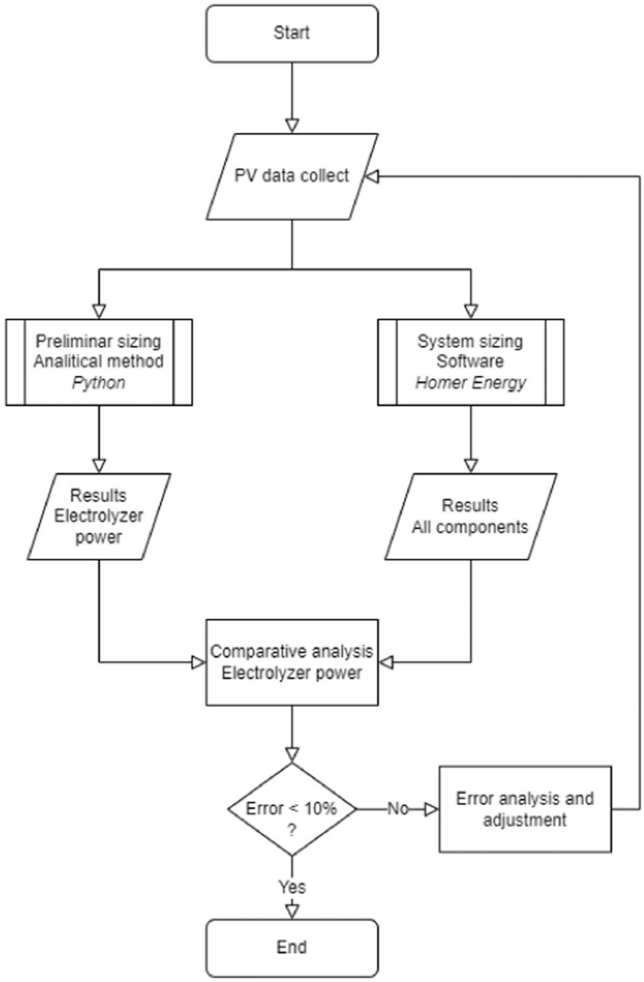

FIGURE 8 Informative flowchart of the sizing path adopted as a model using two electrolyzer sizing methods.

TABLE 1 Data sources.

Data type	Source
Annual energy production	Kaggle database
PV system efficiency	IFBA Irecê campus reports
Electrolyzer efficiency	Manufacturer specifications
Auxiliary consumption	Estimated based on similar studies
Primary load (kWh/day)	Measured data from IFBA Irecê Campus
Energy for 1 kg hydrogen	Calculated based on electrolysis studies

Source: Own authorship.

3. Efficiency of the electrolyzer;
4. Miscellaneous consumption of the electrolysis system;
5. Average primary load in kWh/day; and
6. Data on the energy required to produce 1 kg of hydrogen.

TABLE 2 Electrolyzer sizing results using Python.

Components	Values	Units
Photovoltaic energy generation	142,618.70	kWh/yr
Available energy for electrolyze	121,122.59	kWh/yr
Produced hydrogen	363.71	kg
Hydrogen tank autonomy in hours	3777.5	h/yr
Electrolyzer power	2.25	kW

Source: Own authorship.

4.3.2 | Electrolyzer simulation in HOMER Energy

For simulation in the HOMER Energy, some input data were considered:

1. Data about power plant[36];
2. Solar, wind, and temperature—internal software data (NASA);
3. Efficiency of the electrolyzer;
4. Standard battery—lithium-ion;
5. Standard electrolyzer model; and
6. Standard tank model.

5 | RESULTS AND DISCUSSIONS

A hybrid system was chosen to provide continuous operation for long hours with high efficiency so that the system produces hydrogen on winter and summer days and nights. The results of the analytical modeling performed by the Python software are presented in Table 2.

To carry out the comparative analysis, a simulation was carried out using HOMER software, which serves to identify the best technical and economic parameters of the various energy system equipment based on renewable sources. Thus, depending on the technical specifications of the input data from the PV plant, the program provides the generation produced by the PV plant, the hydrogen production measured in kilograms, the autonomy of the hydrogen tank in hours, the power of the electrolyzer that will be used in the electrolysis process, as well as several graphs that show the behavior of the energy system in the electrolysis process. Figure 9 represents the architectural system for sizing the energy system, and the results are presented in Table 3.

The graph represented in Figure 10 shows the battery state of charge, that is, the parameter applied to the battery cycle charging strategy. We observed that throughout the year, the battery discharges more frequently between 00:00 p.m. and 06:00 a.m. This is

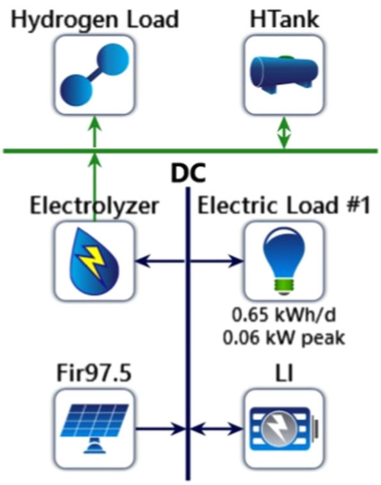

FIGURE 9 System modeling architecture. *Source*: HOMER Energy software.

TABLE 3 Simulation results using Homer energy.

Components	Values	Units
Photovoltaic energy generation	16,682	kWh/yr
Hydrogen tank autonomy in hours	4416	h/yr
Electrolyzer power	2.5	kW

Source: Own authorship.

because the battery is in an operating state to supply energy to the system, that is, from 6 p.m. onward when the PV system is no longer producing energy in full operation. In this way, the storage system regulates power during the day, stabilizing the network. However, the stored energy is only supplied at night and during the early morning hours. In the morning, the PV system returns to full operation with the generation of electrical energy sent to the grid. It can also be seen that the energy storage system's lowest rate was 65% for almost the entire year. As the battery storage system is composing the network, it must continuously operate to keep the electrolyzer running.

For the generation of the PV plant at the Federal Institute of Bahia, Campus Irecê-BA, the simulation results showed that this system requires an electrolyzer with a nominal capacity of 2.5 kW operating with a production of 130 kg/year. In evaluating the results of the Phtyon simulation for sizing the electrolyzer, real data from the electrical energy production of the plant under study was used, and the result was 2.25 kW. This result shows that the analytical modeling in Python predicts a value very close to 2.5 kW by the HOMER Energy software simulation. Therefore, it is understood that for a PV system with an energy of 14,261.87 kWh/year, the size of the electrolyzer required to produce hydrogen is 2.5 kW and requires 4288 h of operation for this production. The energy consumed by the electrolyzer was 10,720 kWh/year with an efficiency of 70% (Figure 11).

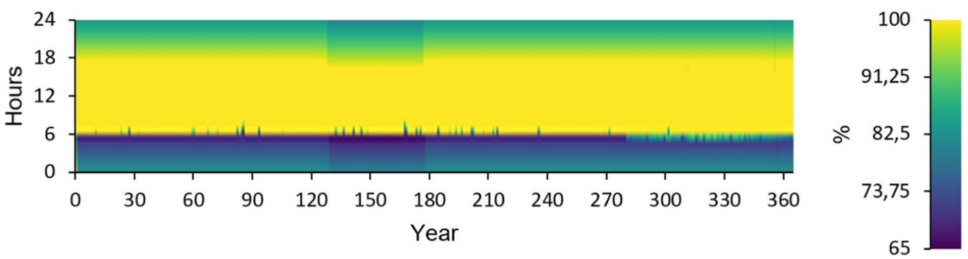

FIGURE 10 Li-ion state of charge (%). *Source*: HOMER software.

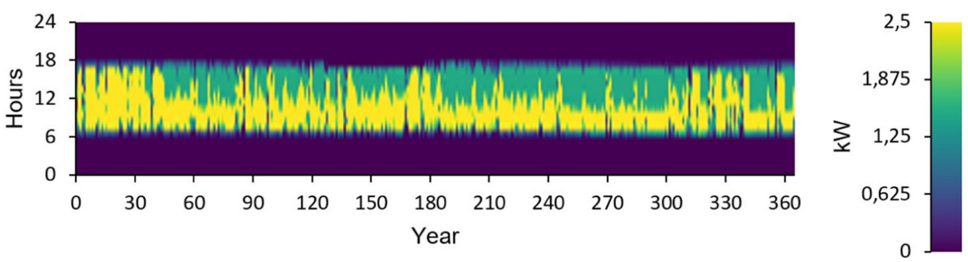

FIGURE 11 Electrolyzer input power (kW). *Source*: HOMER software.

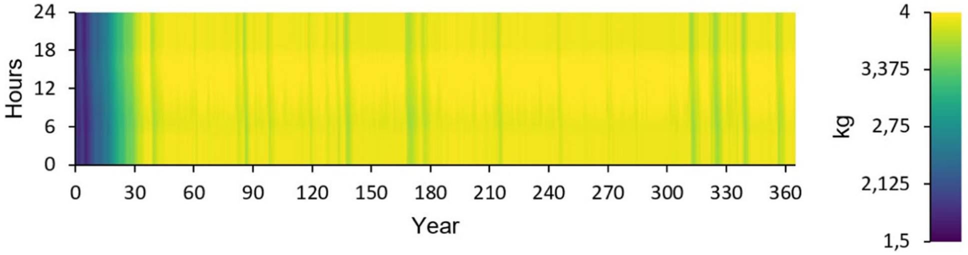

FIGURE 12 Hydrogen tank level (kg). *Source*: HOMER software.

TABLE 4 Hydrogen tank properties.

Quantity	Value	Units
Hydrogen storage capacity	4	kg
Energy storage capacity	133	kWh
Tank autonomy	4923	hr

Source: HOMER software.

Regarding the storage of the hydrogen tank, the simulation resulted in a storage capacity of 4 kg, as can be seen in Figure 12, which translates into an energy reserve of 133 kWh with an autonomy of 4923 h. These values represent the expected operational duration based on system power consumption and hydrogen tank capacity. This is due to the fact that hydrogen is intended for transport and not for local consumption. As the HOMER Pro software does not offer the transport simulation option, hydrogen can be used for other purposes or consumed more quickly, reducing its autonomy, as shown in the results in Tables 3 and 4.

Comparing the results obtained from the electrolyzer size in Python and HOMER Energy, the error percentage for the study was 10%. Therefore, this error can be adjusted using more efficient electrolyzers so that the system design presents an improved performance.

6 | CONCLUSIONS

This study has demonstrated the technical feasibility of employing a PV system for the production of green hydrogen. The system relies primarily on using a renewable source, PV solar energy, integrated with a battery, electrolyzers, and hydrogen tanks. The sizing analysis of the electrolyzer, battery, and hydrogen tank for optimal hydrogen production was effectively conducted using HOMER Energy software.

The results obtained indicate that the proposed PV plant is capable of generating approximately 16,682 kWh/year of electrical energy. The sizing approach reveals that a PV plant with a nominal capacity of 9.36 kWp requires an electrolyzer with a nominal capacity of 2.5 kW, operating with a production of 130 kg/year, and a hydrogen tank with a capacity of 4 kg. This configuration translates into an energy reserve of 133 kWh with an autonomy of 4923 h.

The implementation of this renewable energy system promises a substantial reduction in CO_2 emissions, aligned with global sustainability objectives. The results underscore the importance of employing analytical calculations using the Python programming language and leveraging optimization software for the final size of energy systems. The use of HOMER Energy software, widely recognized and employed for optimizing renewable and hybrid energy systems, including hydrogen production systems, is recognized in the design and optimization of the system.

In future endeavors, as part of ongoing research, the objective is to address much larger-scale energy generation systems. This will involve refining and expanding analytical models to accommodate the intricacies of larger systems, including precise modeling of PV panels and energy converters. This holistic approach ensures that future systems are not only efficient and sustainable but are also scalable to meet the demands of larger energy production scenarios. Furthermore, as larger systems are investigated, considerations will encompass not only technical aspects but also broader systemic implications. This involves investigating the integration of green hydrogen production systems into existing energy infrastructures, understanding the potential impact on energy grids, and optimizing overall performance to meet the demands of a larger consumer base.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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