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Evaluation of Photovoltaic Hydrogen Production Potential Along Highways Connecting the North and Northeast Regions of Brazil

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ABSTRACT

In the present work, the optimized plant for Betim is used as a reference and its hydrogen production capacity is evaluated in the environmental and irradiation conditions along the highways that connect the capitals of the North and Northeast regions, starting in Belém city, in the State of Pará in the North region of Brazil and ending in Salvador city, in the State of Bahia in the Northeast region of Brazil. The two regions object of this study are characterized by high rates of solar irradiation, and, therefore, it is expected that it will be possible to produce a lot of hydrogen per MW of installed power, in each of the mentioned cities. In this context, the reference plant is simulated and evaluated using the HOMER PRO computational code for the environmental conditions of the cities of Belém, São Luís, Teresina, Fortaleza, Natal, João Pessoa, Recife, Maceió, Aracajú and Salvador, with the objective of answering the following research questions: a) how much electricity can be produced with the reference plant in each of the chosen cities? b) what quantity of hydrogen can be produced with the reference plant in each of the chosen cities? And, c) what is the levelized cost of hydrogen produced (LCOH) in each of the selected cities? To answer the research questions, a brief review of electrolysis and photovoltaics was carried out and HOMER PRO was configured and used to perform optimization, simulations and evaluations. Among the results obtained in this work, the possibility of producing hydrogen in the range of 30,170 kg/year to 35,332 kg/year per MW_e installed, in São Luis and Recife, respectively, stands out. In addition, the initial hypothesis that the LCOH along the highway object of this study would be in the range of 2.0 U$/kg to 4.0 U$/kg is fully valid for lower electrolyser costs of 350 US/kW. This work is justified by the fact that it studies the production of hydrogen, a clean fuel, using only water and solar energy, in two regions with potential for the installation of large centralized hydrogen plants. In addition, this work can be used as a reference when choosing a demonstration road in an eventual hydrogen program with decentralized production for the transport sector in Brazil.

KEYWORDS

Hydrogen, Electrolysis, Electrical, Renewable Energy, Photovoltaic Energy, Homer Pro.

INTRODUCTION

Reliance on imported oil from unstable regions of the world has forced the pursuit of hydrogen as a near-future non fossil energy alternative. Electrolysis by solar or wind energy the most practical technical means to eliminate fossil fuels from the energy production cycle, especially when these energies come from the sun. High temperatures and/or electricity can

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also help in this process, enabling countries to use their own renewable electricity and water to produce emission-free hydrogen. There are several advantages to producing hydrogen by electrolysis from solar panels: no moving parts; plug and play; installation at the point of use; virtually maintenance-free; no transportation; and direct production of high-purity hydrogen, and oxygen, among others. There are several companies worldwide that supply equipment for this purpose, some of them claiming reduced production costs without transportation, storage, or compressor requirements.

In a previous work [1], an off grid electrolysis plant powered with photovoltaic energy of 1.0 MW_p in the environmental and solar irradiation conditions around the Gabriel Passos Oil Refinery, located in the city of Betim - MG, was optimized and evaluated, and it was concluded that is possible to produce 35,477 kg of hydrogen per year, with an optimized system equipped with a 1,096 MW photovoltaic (PV) system and electrolyser of 760 kW. The "Betim" plant was simulated for the location with Latitude: 19°;58';57"S and Longitude: 44°;11';57"W, where the monthly average of horizontal global solar irradiation (GHI) is of 5,240 kWh/m²/day. That work also concluded that it is possible to produce green hydrogen with cost of 3.39 U$/kg when considering a discount rate of 8% per year, an inflation rate of 3% per year; the project life was estimated at 20 years; the capital costs of the photovoltaic system was considered in 800.00 U$/kW; the unit cost of the electrolyser estimated in 450.00 USD/kW [1].

Betim is an industrial city in the Metropolitan Region of Belo Horizonte, capital of the State of Minas Gerais, in the southeast region of Brazil, where the Gabriel Passos Oil Refinery (REGAP), owned by Petrobras, operates. REGAP has a processing capacity 155,000 barrels of oil per day, producing Type A gasoline, diesel, marine fuel (bunker), aviation kerosene, liquefied petroleum gas, asphalts, green petroleum coke, fuel oil, sulfur and turpentine; serving a large part of the oil derivatives market. The refinery has an industrial area of 2,305,515 m² where the following main industrial units are installed: two atmospheric and vacuum distillation units; two catalytic cracking units; kerosene hydro desulfurization unit; two diesel hydro desulfurization units; a diesel hydro treatment unit; a cracked naphtha hydrodesulphurization unit; a light coke naphtha hydro treatment unit; cogeneration unit and three hydrogen generation units.

Betim city was chosen for this study for the following reasons: this research is a continuation of a previous work on hydrogen production; in REGAP there are three hydrogen production units from oil and therefore a potential place to produce hydrogen for use as fuel for the transport sector; eventually, Petrobras may be interested in using the plant that is the subject of this study as a pilot plant and use its production, without significant risk; finally, because it is in the same state where the Federal University of Minas Gerais is (where this work has been developed).

In the present work, the optimized plant for Betim is used as a reference and its hydrogen production capacity is evaluated in the environmental and irradiation conditions along the highways that connect the capitals of the North and Northeast regions, starting in Belém city, in the State of Pará in the North region of Brazil and ending in Salvador city, in the State of Bahia in the Northeast region of Brazil. The two regions considered in this study are characterized by high rates of solar irradiation, and, therefore, it is expected that it will be possible to produce a lot of hydrogen per MW of installed power, in each of the mentioned cities.

In this context, the reference plant is simulated and evaluated using the HOMER PRO 3.14.5 a computational code for the environmental conditions of the cities of Belém, São Luís, Teresina, Fortaleza, Natal, João Pessoa, Recife, Maceió, Aracajú and Salvador, with the objective of answering the following research questions: 1) How much energy is it possible to produce with a PV plant of 1,096 kW along the highway considered in this study? 2) At what

LCOE cost? 3) How much hydrogen is it possible to produce? 4) At what LCOH cost? To answer the research questions, a brief review of electrolysis and photovoltaics was carried out and HOMER PRO was configured and used to perform optimization, simulations and evaluations.

The idea of having a hydrogen highway is not new. Some countries have considered this to demonstrate their hydrogen program to the public. For example, an american report dated 2017, in which the California Energy Commission reports the existence of a demonstration highway of the American hydrogen program with 65 hydrogen filling stations, concentrated on the road axis Los Angeles – San Francisco [2]. The capacity of the stations is divided into two classes, one with a capacity between 100 and 180 kg/day of hydrogen, and another with a capacity of 360 kg/day of hydrogen, in which hydrogen is produced in the stations themselves [2]. Thus, the Americans demonstrate the use of hydrogen for the automotive transport sector and test hydrogen production processes.

In Brazil, the first installations of photovoltaic power generation were mentioned for the first time in the BEN - National Energy Balance in 2011, as having an installed capacity of 1.0 MW and since then, it has only grown. In 2015, it was already 21.0 MW, in 2020 it already accumulated 3,297.0 MW and in 2021 it totaled 4,632.0 MW of installed capacity [3]. This demonstrates that photovoltaic energy production is mature enough for a green hydrogen program in Brazil.

Currently, decentralized hydrogen plants are still small [2], with capacities ranging from 180 to 360 kg/day, as they are still built to demonstrate hydrogen systems to the public [2]. However, this research identified several manufacturers of electrolysers capable of producing hydrogen on a large scale with purity greater than 99.99%, with lifetime of 80,000 hours of operations as described in [4-5]; with such electrolyser it is possible to build plants of up to 2.2 MW of capacity [4] with only a single electrolyser, and which, if associated in parallel, can produce hydrogen on a large scale [5-6].

Report presented in 2019 for the G20 (Group of Twenty) [7] shows that:

1) Hydrogen production costs from water electrolysis are influenced by various technical and economic factors, such as: a) CAPEX requirements, b) conversion efficiency, c) electricity costs, d) hours of operation most important yearly, e) capital costs are currently in the range of U$500 - U$1400/kW_e for alkaline electrolysers.
2) The LCOH - Levelized Cost of Hydrogen decreases with increasing hours of electrolyser operation.
3) The low cost of electricity and sufficient quantity to ensure that the electrolyser can operate at full load for a long time are essential for the production of hydrogen at low cost.
4) In electrical systems with increasing shares of renewables, excess electricity can be available at low cost.
5) However, running the electrolyser at full load and using as much electricity as possible could decrease the LCOH cost.

The Figure 1 shows the hydrogen production cost in U$/kg as a function of operating hours, keeping the discount rate at 8% [7-8], electricity cost fixed at 40 U$/MWh [7-9], and the five LCOH cost curves for five capital values versus operating hours, being a curve for electrolyser capital costs in the range from 250 US/kW_e to 650 US/kW_e [7-9]. It is easy to see that for the LCOH cost is in the range of 2.0 U$/kg - 4.0 U$/kg [7-9], starting from 2,000 hours of operation per year, as it is presented by International Energy Agency (IEA) [7-9].

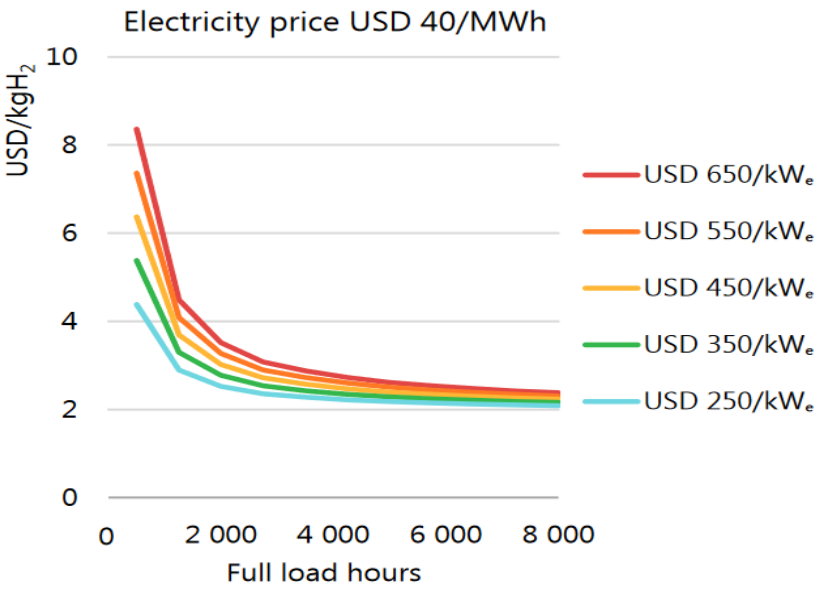


Figure 1. Hydrogen production cost projections [7]

Hypotheses of this work

This work was developed based on the hypothesis that it is possible to produce a lot of hydrogen in the North and Northeast regions of Brazil, with lower production costs than those describe before [7] in the range from 2.0 U$/kg - 4.0 U$/kg, through electrolysis plants powered by photovoltaic energy of 760 kW, considering the following financial assumptions:

a) Electrolyser capital cost of 450 U$/$KW_e$, the average of the IEA simulations [7].

b) Photovoltaic energy at 40 U$/MWh, obtained in simulations with PV of 1,096 kW at capital cost of 900 US/kW [1], c) Discount rate of 8% per year [7-8], d) Inflation of 3% per year [6].

c) Battery for energy storage costs of 200 U$/kWh capacity [8].

d) Sensitivity analysis of the capital cost of the electrolyser for the values of 250 U$/$kW_e$, 350, U$/kW_e, 450 U$/$kW_e$, 550 U$/kW_e and 650 U$/$kW_e$, as it was performed by the IEA [7-9].

Key figures about the highways

Figure 2 shows the layout of the imagined hydrogen road in red linking Belém, capital of the state of Pará, in northern Brazil, crossing the capitals of all states in the northeast region of Brazil, and ending in Salvador, capital of the state of Bahia, totalizing 3,187 km of road. Currently, the selected locations are already interconnected by federal highways with different names. The simulations will be carried out using data from the meteorological stations closest to the highway in the selected locations, which will be automatically located in the HOMER PRO search tool, in the NASA database.

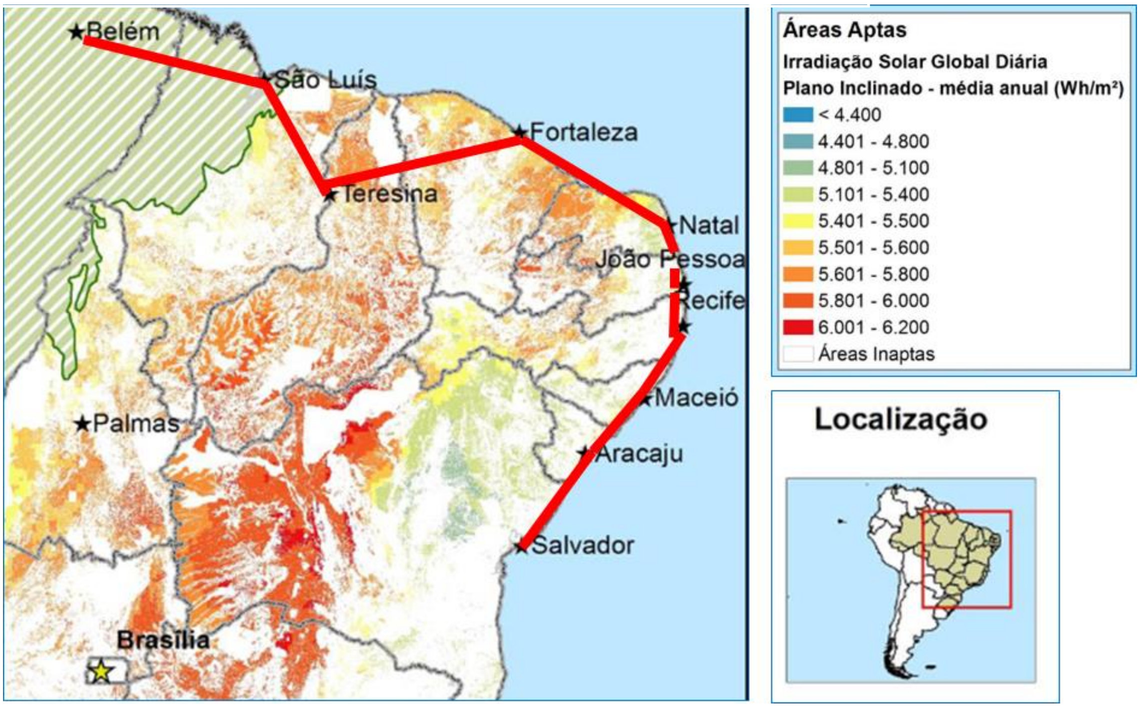


Figure 2. North - Northeast Highway [10]

The Table 1 shows the name of each city in column 1, the geographic position given by altitude and longitude (column 2), the annual average solar irradiance data, in kWh/m² (column 3), and in the fourth column is presented the annual average temperature data (°C) [11].

Table 1. Key data for each site [11] apud [12]

City	Geographic Position	Average Annual GHI (kWh/m^2)	Average Temperature °C
Belém	1°27.4´S; 48°30.1´W	5.05	26.69
São Luís	2°31.8´S;44°17.9´W	4.86	27.04
Teresina	5°4.9´S;42°6.5´W	5.50	27.31
Fortaleza	3°44.0´;38°31.6´W	5.84	26.69
Natal	5°47.1´S;35°12´W	5.58	26.56
João Pessoa	7°7.1´S;34°52.9´W	5.33	26.69
Recife	8°3.5´S;34°53.0´W	5.89	26.18
Maceió	9°40.0´S;35°44.1´W	5.23	25.82
Aracaju	10°55.6´S;37°4.4´W	5.25	25.51
Salvador	12°58.7´S;38°30.1´W	4.92	25.45

Photovoltaic energy

A photovoltaic module is a set of photovoltaic cells interconnected to produce direct current (DC) electricity. A set of conveniently interconnected modules forms a photovoltaic system. The amount of electrical energy produced is a function of the solar irradiance, photovoltaic cell technology and meteorology location, more specifically the ambient temperature that affects the module efficiency [13-14].

This research identified several technologies, brands, models, capacity and technical specifications of photovoltaic systems [13-14]. Regarding the specification, HOMER PRO requires only the following input data: a) system capacity, b) the derating factor, c) the lifetime, d) the effect of temperature on the module power, and the module efficiency [11].
The system capacity is the maximum amount of electricity that the system can produce under ideal conditions (known as 'peak sun'). Sometimes called 'rated capacity' or 'rated output', this is taken to be 1,000 watts (or 1 kW) of sunlight for every square metre of panel [11].
The photovoltaic (PV) derating factor is a scaling factor that HOMER PRO applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated. The HOMER PRO uses the derating factor to account for factors such as panel dirt, wiring losses, shading, snow cover, aging, and so on, during system operation. When one chooses not to include the effect of the temperature of the photovoltaic panel during the simulations, the temperature effect must be added to the derating factor [11]. In this work the effect of the temperature of each location is being considered directly in the calculations.
The HOMER PRO library does not define the PV lifetime, but defines the project lifetime as the period of time during which system costs occur. HOMER PRO uses the project lifetime to calculate annualized costs from current net costs. HOMER PRO assumes that capital recovery values occur at the end of the project's useful life. End-of-life management for photovoltaics (PV) refers to the processes that occur when solar panels and all other components are retired from operation. The estimated operational lifespan of a PV module is about 30-35 years, although some may produce power much longer [15].
The photovoltaic (PV) cell temperature is the temperature of the surface of the PV array. During the night, it is the same as the ambient temperature, but in full sun, the cell temperature can exceed the ambient temperature by 30°C or more. If, in the PV array inputs, you choose to consider the effect of temperature on the PV array, HOMER calculates the cell temperature in each time step and uses it in calculating the power output of the PV array [11].
The photovoltaic (PV) efficiency at standard test conditions is the efficiency with which the PV array converts sunlight into electricity at its maximum power point under standard test conditions. HOMER uses the efficiency to calculate the PV cell temperature. If PV manufacturers don’t report this efficiency in their product brochures, it is possible to calculate it for any PV module using the following Equation (1) [11].

$$\eta_{mp,STC} = \frac{Y_{PV}}{A_{PV}\, G_{T,STC}} \tag{1}$$

Where:
$\eta_{mp,STC}$= efficiency of the PV module under standard test conditions [%]
Y_{PV} = rated power output of the PV module under standard test conditions [kW]
A_{PV}= surface area of the PV module [m^2]
$G_{T,STS}$= radiation at standard test conditions [kW/m^2]

The electrical load of the plant
In HOMER, the term “load” refers to a demand for electric or thermal energy [11-13]. The electrical load of this study is the electrolyser whose power is 760 kW, as defined in previous paragraphs and by assumption.
This research identified several commercial electrolysers that could have been used in this work, however, the authors decided to use a generic electrolyser suggested by HOMER PRO.The technical, economic and restrictions characteristics are assumed as a premise of this work.

The tool HOMER PRO

This work uses HOMER PRO 3.14.5 as a tool to perform the necessary calculations so that the simulations and sensitivity analyzes proposed here are carried out [11].

The HOMER PRO Micro Power Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micro power systems and to facilitate the comparison of power generation technologies across a wide range of applications [13].

It performs the main tasks: simulations, optimization, and sensitivity analysis. In the simulation process, HOMER PRO models a performance of a micro power system configuration each hour of the year to determine its technical feasibility and life-cycle cost. In the optimization process, it simulates many different systems configuration in search of the one that satisfies the technical constrains at the lowest life-cycle cost and determines the optimal value of the variables over which the system design has control such as the mix of components that make up the system and the size or quantity of each. In the sensitivity analysis process, it performs multiple optimizations under a range of inputs assumption to gauge the effect of uncertainty or change in the model inputs [13].

One of HOMER's most powerful features is its ability to do sensitivity analyses on hourly data sets such as the primary electric load or the solar, wind, hydro, or biomass resource[13].

In this work, the modeling of the HOMER PRO computational code simulates the operation of a water electrolysis plant equipped with a 1.0 MW_e photovoltaic system and a 760 MW electrolyser, in ten cities in the North and Northeast regions of Brazil and performs analysis of sensitivity in LCOH as a function of variations in the costs of the electrolyser.

METHOD AND MATERIAL

In this section, the methods adopted to carry out the research and the material and data source used are been presented.

Method

The approach followed in this research is demonstrated in the flowchart represented in the Figure 3, which shows how HOMER PRO is used to fetch data from the environmental conditions of the ten locations in studies and simulate the electric energy and the amount of hydrogen possible to be produced in each of them and their respective leveled costs, necessary to answer the research questions. For this, the approach begins with the division into four stages: 1) Characterization of the studied plant; 2) HOMER PRO configuration; 3) Simulation of the reference plant and optimization for the environmental conditions of each of the 10 selected locations; 4) Sensitivity analysis of results to changes in economic and technical assumptions.

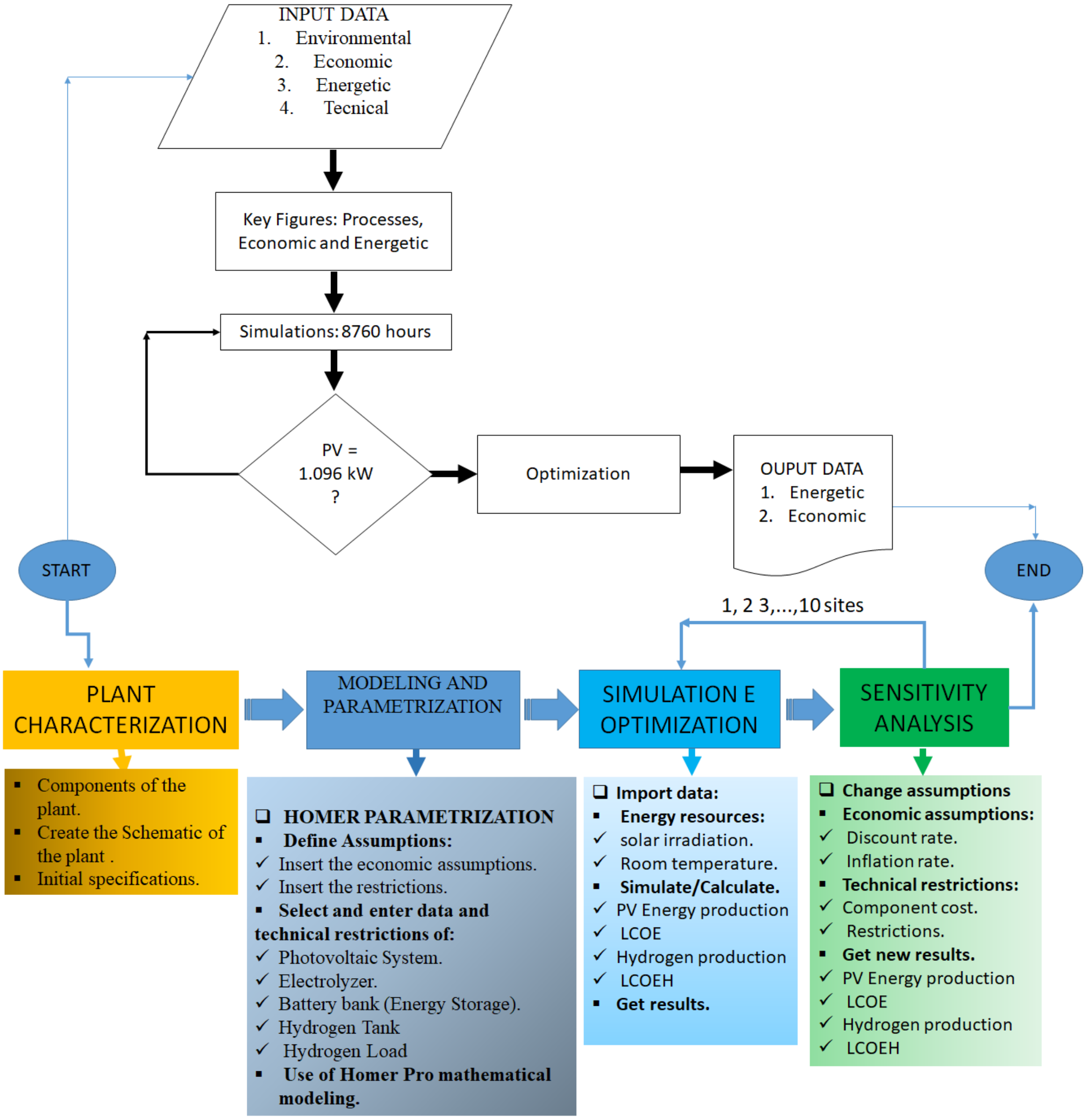


Figure 3. Flowchart of the dynamic simulation and optimization method

Plant Characterization

The plant characterization is the step in which the components of the plant of this study are defined. By assumption [1], it was defined that the plant is an electrolysis plant consisting of the components: a) electrolyser rated capacity of 760 kW; b) photovoltaic system rated capacity of 1,096 kW_p; c) a bank of batteries to store electrical energy in the order of 400 kWh/d for use at times of variation in the intensity of solar irradiation; d) a 100 kg hydrogen tank with capacity to store one day of production, and capacity hydrogen charge, capacity that has already been optimized and simulated in a previous work for the ambient conditions of irradiation and temperature of the city of Betim - MG, site with Latitude: 19°;58';57"S and Longitude: 44°;11';57"W, where the monthly average of global horizontal solar irradiation (GHI) is 5.24 kWh/m²/day. The schematic diagram generated by HOMER PRO is shown in the Figure 4.

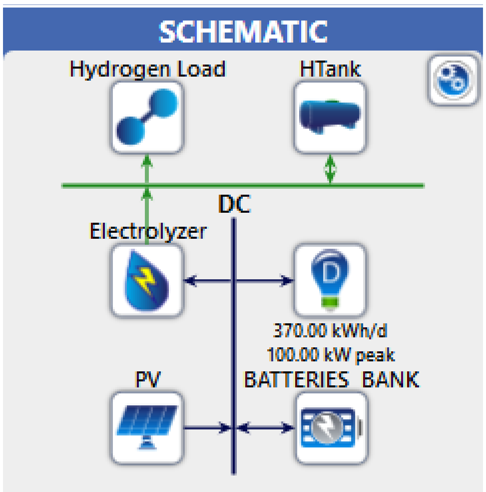


Figure 4. HOMER design of the plant

Modeling

In this step, called modeling, HOMER PRO is parameterized. So, here, the necessary parameters for the execution of the program are defined and presented, which are inserted in each of the program's interfaces by the analyst, such as: assumptions, constraints, characteristics and technical data of each of the components, as shown in the next sections.

Design assumptions

The first parameterization screen of HOMER PRO refers to the design assumptions. In this study, the initial configuration will be done according to the indicators shown in Table 2, where you can see the name of the data to be inserted, the unit of measurement, and the value to be adopted and the reference document. As this is the initial parameterization, the values are only reference values. New values will be adopted in the step that deals with the sensitivity analysis.

Table 2. Design assumptions

Data name	Unit	Value	Source
Discount rate	%	8.0	[5-7]
Inflation rate	%	3.0	[6]
Annual capacity shortage	%	50	Assumption
Project life time	Years	25	[5-7]

Constraints

This work aims to simulate a plant powered exclusively by a photovoltaic system. So, all the energy used in the process is (100%) from a solar energy source, and being solar, half of the year is in operation (during the day) and half of the year is in black-out (without energy at night), in case there is no storage system for electricity. Previous work has shown that using a battery bank makes the hydrogen produced much more expensive than systems without an energy storage system. The plant under study is off grid where the PV system is the only source of energy, so the minimum fraction of renewable energy is 100% renewable, and the fraction of solar energy is 100%. The maximum annual capacity shortage initially specified was 50%, considering that the plant is powered only by photovoltaic energy, and therefore accepts energy shortages 50% of the time. However, HOMER PRO optimizes this value for each site, during the respective simulations and reports at the end of each one of them. So, initially, the assumed design constraints are those shown in Table 3.

Table 3. Constraints assumptions

Data name	Unit	Value	Source
Minimum renewable fraction	%	100	Assumption
Annual peak load	%	100	Assumption
Solar power output	%	100	Assumption

Technical data and assumption of photovoltaic system

As described in the previous section of this work, there is a huge range of photovoltaic systems that can be used in the simulations provided for in this work. In the HOMER PRO library itself, there are several photovoltaic systems available and with well-defined technical specifications, whose characteristics can be easily loaded into the computational code and easily run the simulations and evaluations provided for in this work.

Among numerous commercial in Brazil or imported mainly from China, solar energy is readily accessible for producing electricity in off grid systems. The power generated by the PV module is proportional to the location's Solar Radiation quantity. In the simulations carried out in this work, the generic photovoltaic system alternative offered by the HOMER PRO library and the specifications and restrictions shown in the Table 4 were used.

Table 4. Data for photovoltaic system

Data name	Unit	Value	Source
Capital Costs	U$/kW	900	Assumption [1]
Replacement Costs	U$/kW	900	Assumption [1]
O&M Costs	U$/year	9.00	Assumption [1]
Life time	years	25	[2]
Derating Factor	%	96	Assumption [11]
Rated Capacity	kW	1,096	Assumption [1]

The photovoltaic (PV) derating factor is a scaling factor that HOMER applies to the PV array power output to account for reduced output in real-world operating conditions compared to the conditions under which the PV panel was rated. Use the derating factor to account for such factors as soiling of the panels, wiring losses, shading, snow cover, aging, and so on. If the analyst does not explicitly model the effect of temperature on the PV array, it is necessary to include temperature-related effects in the derating factor.

Technical data and assumption of electrolyser

An electrolyser consumes electricity to generate hydrogen via the electrolysis of water [23]. In HOMER, the user specifies the size of the electrolyser, which is a decision variable, in terms of its maximum electrical input. The user also indicates whether the electrolyser consumes AC or DC power, and the efficiency with which it converts that power to hydrogen. HOMER defines the electrolyser efficiency as the energy content of the hydrogen produced divided by the amount of electricity consumed. The final physical property of the electrolyser is its minimum load ratio, which is the minimum power input at which it can operate, expressed as a percentage of its maximum power input. The economic properties of the electrolyser are its capital and replacement cost in dollars, its annual O&M cost in dollars per year, and its expected lifetime in years [23]. HOMER PRO does not have a database with the technical specifications of commercial electrolysers available on the market. Thus, a generic electrolyser with a rated capacity of 760 kW will be used, as explained in the previous section. Other hypotheses adopted for the electrolyser in this study are presented in Table 5.

Table 5. Data assumptions for generic electrolyser

Data name assumption (Constraints)	**Unit**	**Value**	**Source**
Capacity Optimization	kW	760	Assumption [1]
Efficiency	%	74	[7-8]
Life time	years	15	[15]
Capital Costs	U$/kW	450	[15]
Replacement Costs	U$/kW	450	[15]
O&M Costs	%/year	1%	Assumption [1]

Batteries bank

In the HOMER PRO library, several batteries ready to be used are available, integrated with a photovoltaic system and with well-defined technical specifications, whose characteristics can be easily loaded into the computational code and easily run the simulations and evaluations foreseen in this work.

In the simulations carried out in this work, generic batteries from the HOMER PRO library were used, with the following technical specifications: nominal voltage of 12 volts; 1.0 kWh of storage capacity, maximum capacity of 83.4 Ah; capacity ratio of 0.403; rate constant of 0.827 per hour; round-trip efficiency rated at 80%; maximum charge current of 16.7 A; maximum discharge current of 24.3 A; maximum charge rate of 1.0 A/Ah [11]. In addition, for the battery bank used in this work, the assumptions and constraints shown in Table 6 were adopted and configured in HOMER PRO.

Hydrogen storage

As this work aims to estimate the amount of hydrogen produced over a year, it was necessary to configure a generic tank of 50,000 kg, with the capacity to store all the hydrogen produced in electrolysis plant of 1.0 MW_e. However, the plant's hydrogen tank when in commercial production will be 100 kg, destined only to store the surplus produced and not consumed in the demonstration and commercial operation phases. Thus, the amount of capital considered in the cost simulations was the same, with the necessary adjustments in the unit costs of capital. In addition, it was also considered that the tank will have a useful life of 25 years, and will start each operation cycle in the empty condition and that at the end of each year, the total amount of hydrogen will be the produced amount added to the initial amount.

Table 6. Data assumptions for batteries bank

Data name assumption (Constraints)	Unit	Value	Source
String size	-	20	Assumption [1]
Voltage	V	220	Assumption [1]
Initial State of Charge	%	100	Assumption [1]
Minimum State of Charge	%	20	Assumption [1]

Throughput	kWh	100	Assumption [1]
Life time	year	4	[11]
Capital Costs (average)	U$/Unit.	200	[7-8]
Replacement Costs	U$/Unit.	200	[7-8]
O&M Costs	U$/kW/year	2	[7-12]

Hydrogen load

In HOMER PRO, the hydrogen load represents an external demand for hydrogen. The electrolyser can meet this demand with the primary electrical generated by the Photovoltaic system of the own plant. In this work, the hydrogen flow optimized by HOMER PRO for each of the locations for the period from 07:00h to 18:00h was inserted, as shown in table 7. In addition, the following assumptions were defined and inserted on HOMER PRO: Maximum unmet hydrogen load: 0%; Unmet Hydrogen load penalty 0 U$/kg; Value of electricity: 0 $/kg, since the plant has its own power generation.

Simulations and optimization

In this stage, the simulations and optimizations of the plant are carried out considering the environmental conditions of each location, the algorithm and the mathematical modeling of HOMER PRO, to obtain the answers to the research questions, which are calculated according to the modeling and plant optimizations are carried out considering the environmental conditions of each location, the HOMER PRO algorithm and mathematical modeling.

Environmental conditions of solar irradiation

HOMER uses the Solar Global Horizontal Irradiation (GHI) feature to calculate the flat panel PV array output. GHI is the sum of beam radiation (also called direct normal irradiance or DNI), diffuse irradiance, and ground-reflected radiation. The GHI calculation process is not demonstrated here, but the interested reader can seek to understand it by accessing [11].

HOMER accepts solar radiation data as monthly averages or as a time series. Time series solar radiation data is most commonly available with an hourly time step, but HOMER can accept any time step down to one minute. In this study is used the NASA's Surface Solar Energy Data Set that provides monthly average solar radiation data for everywhere on earth at http://eosweb.larc.nasa.gov/sse [11].

Calculation of the PV array out put

The Solar GHI Resource page allows specifying the global horizontal radiation (GHI) for each time step in the HOMER simulation. The GHI is the total amount of solar radiation striking the horizontal surface on the earth. But the power output of the PV array depends on the amount of radiation striking the surface of the PV array, which in general is not horizontal. So in each time step, HOMER must calculate the global solar radiation incident on the surface of the PV array [11].

HOMER uses the Equation (2) to calculate the output of the PV array [11]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STD}}\right)\left[1 + a_P\left(T_c - T_{c,STC}\right)\right] \tag{2}$$

Where:

Y_P = the rated capacity of the PV array, meaning its power output under standard test conditions [kW].

f_{PV} = derating factor [%].

G_T= solar radiation incident on the PV in the current time step [kW/m^2].

$G_{T,ST}$= incident radiation at standard test conditions [1.0 kW/m^2].

a_P= cell temperature coefficient of power [%/°C].

T_c = PV cell temperature in the current time step [°C].

$T_{c,STC}$ = PV temperature under the standard test conditions [25°C].

The photovoltaic (PV) cell temperature is the temperature of the surface of the PV array. During the night, it is the same as the ambient temperature, but in full sun, the cell temperature can exceed the ambient temperature by 30°C or more [11].

If, in the PV array inputs, you choose to consider the effect of temperature on the PV array, HOMER calculates the cell temperature in each time step and uses it in calculating the power output of the PV array [11]. Otherwise, it assumes that the temperature coefficient of power is zero, so the Equation (2) is simplified (3) [11]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STD}}\right) \tag{3}$$

Calculation the electric energy produced

P_{PV} is power, and it is measured in kW. Then, the energy produced is calculated by multiplying P_{PV} by Δt, which is the time at which P_{PV} occurs. In this work, HOMER PRO calculates the electricity produced each year at kWh, which can generally be expressed as follows in Equation (4):

$$E_{PVout} = \int_0^{t1} P_{PV}\,\mathrm{dt} + \int_{t1}^{t2} P_{PV}\,\mathrm{dt} + \ldots + \int_{tn}^{8760} P_{PV}\,\mathrm{dt} \tag{4}$$

Calculation of LCOE - Levelized Cost of Energy

HOMER defines the levelized cost of energy (LCOE) as the average cost per kWh of useful electrical energy produced by the system. To calculate the LCOE, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total electric load served, using the following Equation (5) [11]:

$$\mathrm{LCOE} = LCOE = (C_{ann,tot} - C_{boiler} H_{served}) / E_{served} \tag{5}$$

Where:

$C_{ann,tot}$ = total annualized cost of the system [U$/yr].
C_{boiler} = boiler marginal cost [$/kWh].
H_{served} = total thermal load served [kWh/yr].
E_{served} = total electrical load served [kWh/yr].

The second term in the numerator is the portion of the annualized cost that results from serving the thermal load. In this study systems, such as wind or PV, that do not serve a thermal load ($H_{thermal}$=0), this term is zero.

The total annualized cost is the annualized value of the total net present cost. The HOMER PRO calculates the total annualized cost using the following Equation (6) [11]:

$$C_{ann,tot} = CRC(i, R_{proj}).C_{NPC,tot} \tag{6}$$

Where:
$C_{NPC,tot}$ = total net present cost [U$].
I = annual real discount rate [%].
R_{proj}= project lifetime [year].
CRC( ) = a function returning the capital recovery factor.

Calculation of the hydrogen produced
The HOMER PRO calculates hydrogen production by the electrolyser efficiency, that is the efficiency with which the electrolyser converts electricity into hydrogen. It is equal to the energy content (based on the Higher Heating Value - HHV) of the hydrogen produced divided by the amount of electricity consumed [11].

Calculation of the LCOH - Levelized Cost of Hydrogen

HOMER PRO uses Equation (7) to calculate the LCOH - Levelized Cost of Hydrogen [11].

$$\text{LCOH} = [C_{ann} - V_{elet}(E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales})]/M_{hydrogen} \tag{7}$$

Where:

$C_{ann,tot}$ = total annualized cost of the system [U$/year].

V_{elet} = electric energy cost value [$/kWh].

$E_{prim,AC}$= primary energy load [kWh/year].

$E_{primary,DC}$ = total electrical load served [kWh/year].

E_{def}= deferrable energy [kWh/year].

E_{grid} = energy from grid [kWh/year].

In this study, all the energy served is produced by the plant's own voltaic system. So, the second term of the numerator is zero.

Get results from simulations, optimization and sensitivity analysis

The results obtained by HOMER PRO are made available to the analyst in several data-rich reports. In these studies, only the data necessary to answer and analyze the research questions are used.

Sensitivity analysis

Although the technologies considered in this study are evolving in terms of maturity, the capital costs of the equipment tend to be reduced over time, the business environment in Brazil is not stable and changes with each government and this results in changes in the levels of inflation rate and discount rate. Moreover, the learning curve in the operation and maintenance of energy systems in general results in better operational performance of these systems; the, it was decided, for reasons of objectivity, obtain results and sensitivity analysis only at the capital cost of the electrolyser.

Material

The material for this research is the Monthly Average Solar Global Irradiance and the Monthly Average Temperature Data of each site, which HOMER PRO downloads from the NASA database and then converts into electrical energy, which in turn, is converted into hydrogen by the process of electrolysis, using the algorithm and mathematical modeling of its own computational code. The Figures 7, 8, 9 and 10, by way of example, show the research material for the site in the vicinity of Recife city.

The Figure 5 shows the Global Hourly Average of Solar Irradiance for the 365 days of the year. It can be seen that there is sun every day of the year from 06:00h to 18:00h, with some occurrences of sun starting at 5:00h.

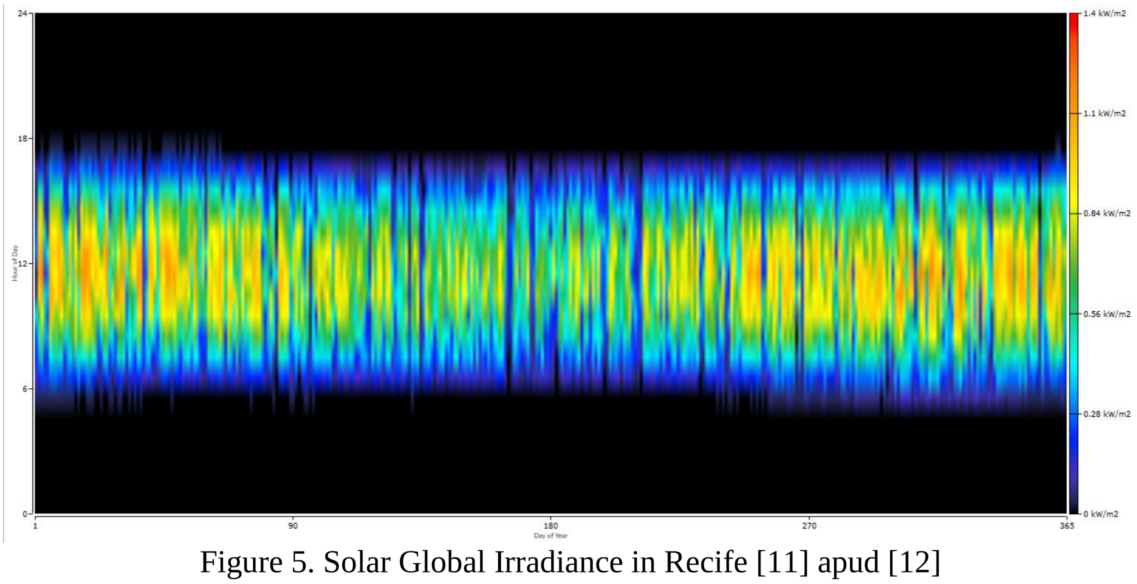


Figure 5. Solar Global Irradiance in Recife [11] apud [12]

Figure 6 shows the Monthly Global Solar Averages in Recife for the 12 months of the year. It is easy to see that the highest incidence of solar irradiation occurs in november of each year, with a maximum annual irradiance value of 1.24 kWh/m^2, maximum daily average of 1.0 kWh/m^2, average 0.28 kWh/m^2 and minimum 0.0 kWh/m^2; and that the lowest incidence occurs in june of each year, with an annual maximum of 0.97 kWh/m^2, maximum daily average of 0.72 kWh/m^2, average of 0.19 kWh/m^2, and the minimum is 0.0 kWh/m^2 [11] apud [12].

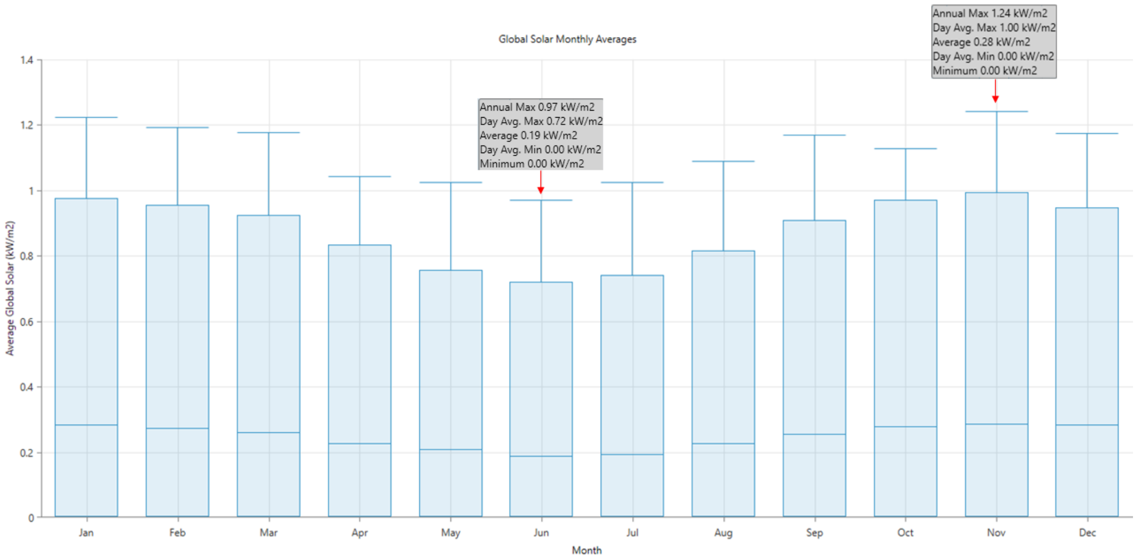


Figure 6. Global Solar Monthly Averages in Recife

Figure 7 shows the graph of the Monthly Average Temperature in Recife, where it is easy to see that the average annual temperature is 26.18°C, the minimum temperature is 24.62°C and occurs in the month of august of each year and the maximum temperature is 27.36°C and occurs in the month of march [11] apud [12].

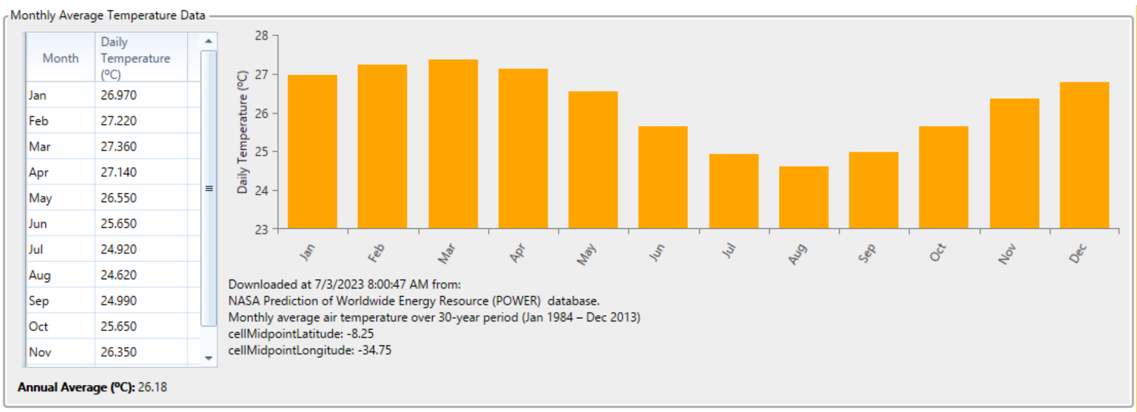


Figure 7. Ambient temperature in Recife [11] apud [12]

The Figure 8 shows the Global Solar Incident Daily Profile for Recife for all the months of the year.

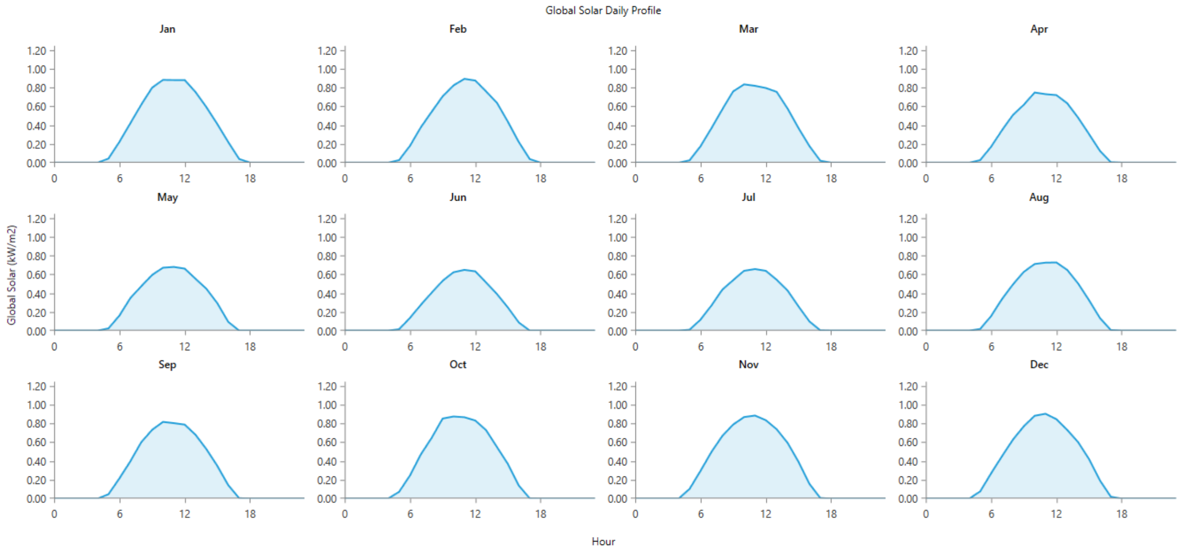


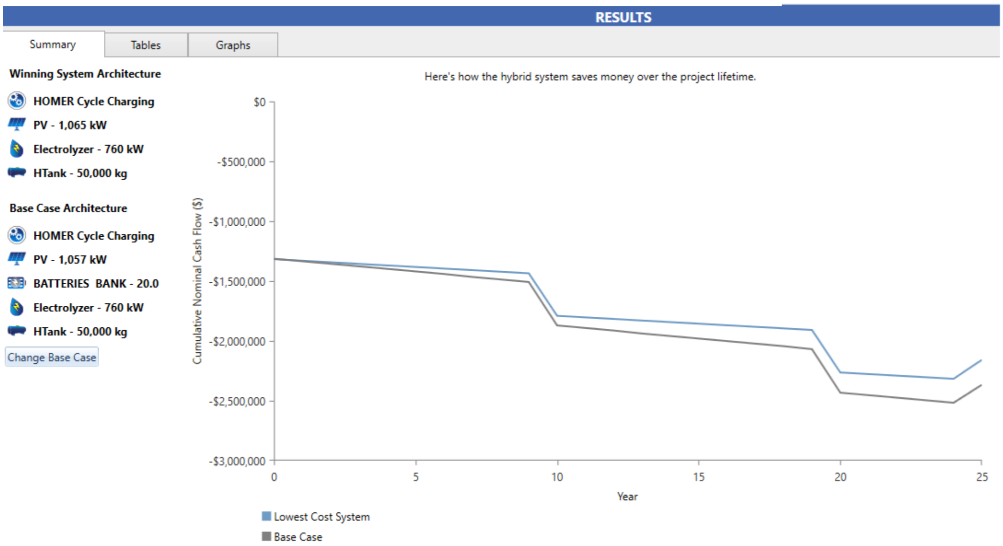
Figure 8. Global Solar Incident Daily Profile [11] apud [12]

RESULTS

The results of this research are presented in the next sections, and aim to answer the questions proposed at the beginning of the research.

Optimization results

HOMER PRO made several simulations for each location, including those shown in Figure 9, which refers to the Recife site with electrolyser capital costs of 450 U$/kW, where it can be seen that the battery bank raises the cost of hydrogen production, causing LCOH to grow from 3.65 U$/kg, in the plant without a battery bank, with the plant operating only during sunny hours or capacity annual shortage of 50%, to 8.03 U$/kg in the plant equipped with 840 batteries, necessary for the plant to operate with a minimum annual capacity shortage. Likewise, this performance trend was verified for all simulations on the other sites.
So, the plant object of this study becomes a purely photovoltaic plant, therefore without a battery bank.



Architecture			Cost			System		PV	
PV (kW)	BATTERIES BANK	Electrolyzer (kW)	NPC ($)	COE ($)	Initial capital ($)	Elec Prod (kWh/yr)	Excess Elec (kWh/yr)	Production (kWh/yr)	LCOH U$/kg($H_2$)
1,065		760	$1.80M	$0.992	$1.32M	2,195,654	185,647	2,195,654	3.65
1,080		760	$1.81M	$1.00	$1.33M	2,227,942	200,100	2,227,942	
1,096		760	$1.83M	$1.01	$1.34M	2,260,232	215,157	2,260,232	
1,127		760	$1.86M	$1.03	$1.37M	2,324,810	246,645	2,324,810	
1,057	20	760	$1.92M	$1.06	$1.31M	2,179,509	181,441	2,179,509	3.82
1,065	20	760	$1.93M	$1.06	$1.32M	2,195,654	188,651	2,195,654	
1,190		760	$1.93M	$1.06	$1.43M	2,453,966	315,764	2,453,966	
1,080	20	760	$1.94M	$1.07	$1.33M	2,227,942	203,400	2,227,942	
1,252		760	$1.99M	$1.10	$1.49M	2,583,122	389,762	2,583,122	
1,378		760	$2.12M	$1.17	$1.60M	2,841,434	552,137	2,841,434	
1,065	60	760	$2.18M	$1.11	$1.33M	2,195,654	183,831	2,195,654	4.35
1,096	60	760	$2.21M	$1.12	$1.36M	2,260,232	213,350	2,260,232	
1,503		760	$2.25M	$1.24	$1.71M	3,099,746	727,746	3,099,746	
1,503		760	$2.25M	$1.24	$1.71M	3,099,746	727,746	3,099,746	
1,065	100	760	$2.44M	$1.17	$1.34M	2,195,654	182,310	2,195,654	4.88
1,127	100	760	$2.50M	$1.20	$1.39M	2,324,810	243,586	2,324,810	
1,190	100	760	$2.56M	$1.23	$1.45M	2,453,966	311,642	2,453,966	
1,127	200	760	$3.14M	$1.33	$1.41M	2,324,810	239,655	2,324,810	6.12
1,252	220	760	$3.40M	$1.41	$1.53M	2,583,122	379,733	2,583,122	
1,378	220	760	$3.52M	$1.46	$1.64M	2,841,434	540,282	2,841,434	6.19
1,252	420	760	$4.42M	$1.70	$1.57M	2,583,122	372,858	2,583,122	
1,503	420	760	$4.68M	$1.79	$1.80M	3,099,746	704,424	3,099,746	7.95
1,503	840	760	$4.72M	$1.81	$1.88M	3,099,746	706,943	3,099,746	8.03

Figure 9. Plant architecture evaluation

Amount and LCOE of produced energy at each site

Table 7 shows, in the first column, the name of each site where the plant was simulated, the geographic position according to the latitude and longitude of each site, in the second column, the amount of energy produced per year in each site and the cost of energy produced in the third and fourth column, respectively.

Amount hydrogen and LCOH of produced hydrogen in each site

The Table 8 shows the name of each of the sites in the first column, the amount of hydrogen produced in the second column, the levelized costs of the hydrogen produced as a function of the capital cost of the electrolyser ranging from 650 U$/kW, 550 U$/kW, 450 U$/kW, 350 U$/kW and 250 U$/kW, in the third, fourth, fifth, sixth and seventh column, respectively.

Table 7. Energy produced in each site

Site City	Geographic Position	Production kWh/Year	LCOE U$/MWh
Belém	1°27.4´S; 48°30.1´W	1,849,580	43.40
São Luís	2°31.8´S;44°17.9´W	1,864,572	42.30
Teresina	5°4.9´S;42°6.5´W	2,141,324	36.80
Fortaleza	3°44.0´;38°31.6´W	2,102,085	37.50
Natal	5°47.1´S;35°12´W	2,143,078	36.80
João Pessoa	7°7.1´S;34°52,9´W	2,044,937	38.60
Recife	8°3.5´S;34°53.0´W	2,195,654	34.90
Maceio	9°40.0´S;35°44.1´W	2,035,033	39.30
Aracaju	10°55.6´S;37°4,4´W	2,021,552	39.00
Salvador	12°58.7´S;38°30.1´W	1,849,802	41.60

Table 8. Hydrogen produced and LCOH in each site

		LCOH	LCOH	LCOH	LCOH	LCOH
Site	Production	650 U$/kW	550 U$/kW	450 U$/kW	350 U$/kW	250 U$/kW
City	kg/year	U$/kg	U$/kg	U$/kg	U$/kg	U$/kg
Belém	30,489	4.94	4.59	4.24	3.90	3.55
São Luís	30,170	4.94	4.59	4.24	3.90	3.55
Teresina	34,377	4.34	4.03	3.72	3.41	3.11
Fortaleza	34,446	4.33	4.02	3.72	3.41	3.10
Natal	34,512	4.32	4.02	3.71	3.40	3.09
João Pessoa	32,973	4.53	4.20	3.88	3.56	3.24
Recife	35,332	4.16	3.86	3.56	3.26	2.95
Maceio	32,400	4.64	4.31	3.98	3.66	3.33
Aracaju	32,575	4.58	4.26	3.93	3.60	3.28
Salvador	30,191	4.88	4.53	4.17	3.82	3.47

Operating time at each site

Table 9 shows the operating time of the PV system and the electrolyser, where it can be seen that the photovoltaic system remains the longest and shortest operating time in Teresina and Salvador, with 4,407 hours/year and 4,317 hours/year respectively. However, it is in Recife that the electrolyser is kept in operation the longest, with 3,731 hours, and it is in São Luis where the electrolyser operates the least time, with only 3,438 hours.

Since the rated power of the power system is greater than the power of the electrolyser, and since the power system operates longer than the electrolyser, there is electricity excess. This excess is shown in Table 10.

Electricity Excess

Table 10 shows that in Teresina the energy excess is greatest with amount of 199,448 kWh/year. The lowest energy excess occurs in Belem, where the excess energy is only 119,273 kWh.

Table 9. PV and Electroliser operating time

Site City	PV hours/year	Electroliser hours/year
Belém	4,380	3,532
São Luís	4,380	3,438
Teresina	4,407	3,581
Fortaleza	4,337	3,633
Natal	4,382	3,698
João Pessoa	4,393	3,650
Recife	4,387	3,731
Maceio	4,329	3,599
Aracaju	4,300	3,592
Salvador	4,317	3,495

Table 10. Electricity Excess per site

Site City	Excess Energy kWh/year
Belém	119,273
São Luís	150,775
Teresina	199,448
Fortaleza	157,766
Natal	194,793
João Pessoa	178,457
Recife	185,647
Maceio	182,451
Aracaju	177,616
Salvador	141,332

ANALISYS

Amount Energy Produced Analysis

The Figure 10 shows two graphs. Graph A shows and compares the total amount of energy produced at each site per year and the difference between each site and the site with the lowest production. It is easy to see that the site with the highest production is in Recife, while the one with the lowest production is in Belem. Graph B presents the same results as Graph A, but in a different way.

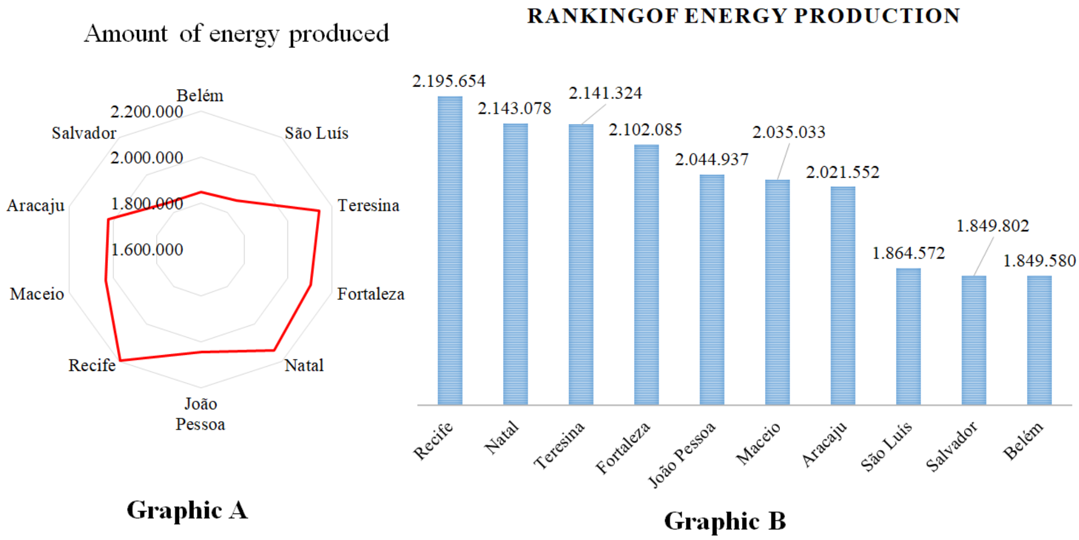


Figure 10. Produced energy analysis

Amount hydrogen produced analysis

The Figure 11 shows two graphs. Graph C, shows and compares the total amount of hydrogen produced at each site per year and the difference between each site and the site with the lowest production. It is easy to see that the site with the highest production is in Recife, while the one with the lowest production is in São Luis.

The graph D, shows the Ranking according to hydrogen production; it is easy to see that the first Ranking is the Recife site with 35,332 kg of hydrogen per year, followed by Natal and Fortaleza in second and third position; the site with the lowest production and last in the Ranking is São Luis with 30,170 kg of hydrogen per year.

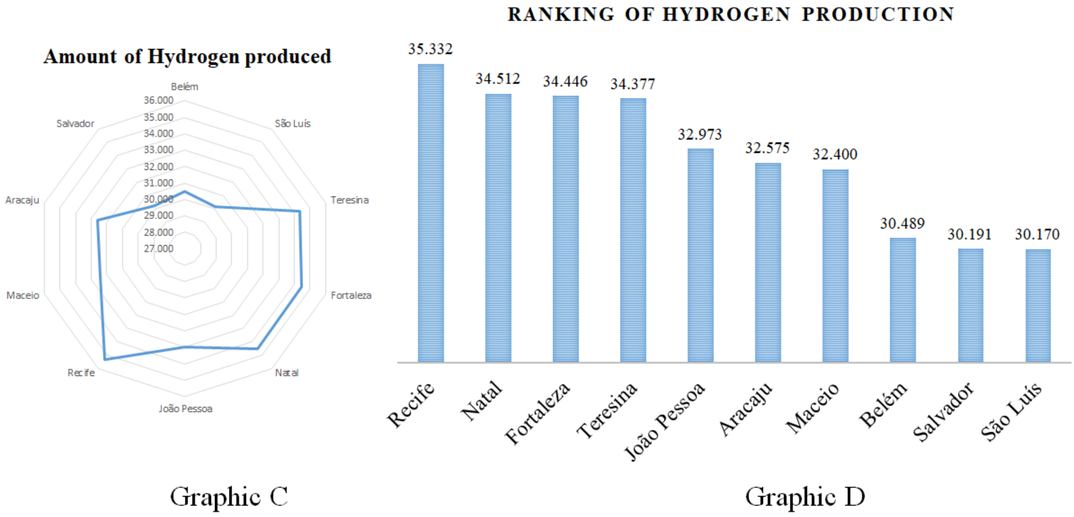
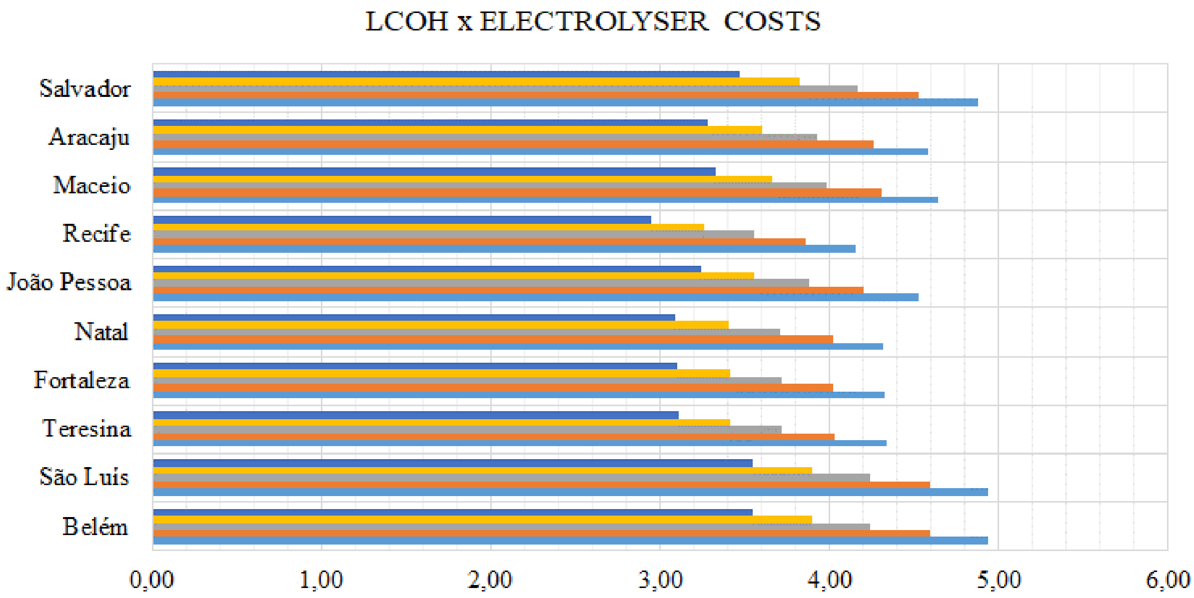


Figure 11. Produced Hydrogen Analysis

Hydrogen production costs analysis

Figure 12 shows a graph of the cost of hydrogen production, through its LCOH at each of the sites as a function of the capital cost of the electrolyser. On the X axis you can see the LCOH, on the Y axis the location, and the lines represent the LCOH for the different values of the electrolyser capital cost.



	Belém	São Luis	Teresina	Fortaleza	Natal	João Pessoa	Recife	Maceio	Aracaju	Salvador
250 $/kW	3,55	3,55	3,11	3,10	3,09	3,24	2,95	3,33	3,28	3,47
350 U$/kW	3,90	3,90	3,41	3,41	3,40	3,56	3,26	3,66	3,60	3,82
450 $/kW	4,24	4,24	3,72	3,72	3,71	3,88	3,56	3,98	3,93	4,17
550 U$/kW	4,59	4,59	4,03	4,02	4,02	4,20	3,86	4,31	4,26	4,53
650 U$/kW	4,94	4,94	4,34	4,33	4,32	4,53	4,16	4,64	4,58	4,88

Figure 12. LCOH (U$/kg(H2) x Electrolyser Capital Costs (U$/kW)

From Figure 12, it is possible to draw the following conclusions regarding the cost of hydrogen production in Brazil:

a) The lowest LCOH were obtained for the Recife site, in the range of 2.95 U/kg to 4.16 U$/kg, for electrolyser costs in the range of 250 U$/kW and 650 U$/kW, respectively.

b) The worst LCOH costs were obtained at the Belem and São Luis sites, in the range of 3.55 U$/kg to 4.94 U$/kg, for electrolyser costs in the range of 250 U$/kW and 650 U$ $/kW, respectively.

c) For the median cost of the electrolyser, with electrolyser at 450 U$/kW, the lowest cost occurred at the Recife site at a cost of 3.56 U$/kg and the highest cost was 4.24 U$/kg, at the Belem and São Luis sites.

d) For electrolyser capital cost at 250 U$/kW or 350 U$/kW the LCOH is less than 4.00 U$/kg at all sites.

e) For the capital cost of the electrolyser at 450 U$/kg, the LCOH exceeds 4.00 U$/kg at the sites in Belém, São Luís and Salvador.

f) For the capital cost of the electrolyser at 550 U$/kg, only in Recife the LCOH was less than 4.0 U$/kg.

g) For electrolyser capital cost at 650 U$/kW, LCOH exceeds 4.0 U$/kg at all sites.

So, it is possible to conclude that the initial hypothesis that the LCOH along the highway object of this study would be in the range of 2.0 U$/kg to 4.0 U$/kg is fully valid for electrolyser costs lower than 350 US/ kW.

CONCLUSION

This work fulfilled the initially foreseen scope, simulating and evaluating an electrolysis plant powered by photovoltaic energy, equipped with a PV system of 1,096 kW and electrolyser of 760 kW, for the environmental conditions of ten sites connected by highways connecting the North to the Northeast of Brazil, and considering the restrictions and assumptions established throughout the work, it is possible to conclude that:

1) It is possible to produce a lot of electricity along the highways that connect the North to the Northeast of Brazil, since in this work the possibility of producing in the range of 1,849,580 kWh in Belém and 2,195,654 kWh in Recife was obtained, as shown in column C of Table 7 and so, answering the first question of this research.
2) It is also possible to produce energy at a cost of 40 U$/MWh - IEA assumption. The simulations carried out here and shown in the fourth column of Table 7, allow us to conclude that it is possible to produce energy in the range of 34.9 U$/MWh in Recife and 43.40 U$/MWh in Belém, an average of 39.02 U$/MWh and median of 38.80 U$/MWh in Teresina. This answers the second question of this research.
3) It is possible to produce a lot hydrogen along the highways that connect the North to the Northeast of Brazil, since in this work the possibility of producing in the range of 30.170 kg per year in São Luis and 35.332 kg per year in Recife was obtained, as shown in Table 8 and so, answering the thirty question of this research.
4) Figure 12 shows that the initial hypothesis that the LCOH along the road object of this study would be in the range of 2.0 U$/kg to 4.0 U$/kg is fully valid for lower electrolyser costs at 350 US/kW.
5) In addition to answering the research questions, it is also possible to conclude:
   a) The battery capital cost of 200 U$/unit, with replacement every four years, increases the cost of hydrogen production to remove the attractiveness of plants with energy storage, as shown in Figure 9.
   b) There was excess energy at all sites, as per Table 10.

Finally, the authors wish to recommend that the hypothesis of this work be tested, in the vicinity of the same evaluated sites, considering:
a) Wind energy.
b) Hybrid wind and photovoltaic energy.

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NOMENCLATURE

BEN - National Energy Balance.
CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior
CAPEX - Capital Expenditure.
CNPq - Conselho Nacional de Desenvolvimento Científico e Tecnológico.

DC - Direct Current.
FAPEMIG - Fundação de Amparo à Pesquisa do Estado de Minas Gerais.
G20 - Group of Twenty.
GHI - Horizontal Global Irradiation.
HOMER PRO - Homer Pro, or HOMER (Hybrid Optimization of Multiple Electric Renewables).
HVV - Higher Heating Value
IEA - International Energy Agency.
LCOE - Leveled Cost of Energy.
LCOH - Leveled Cost of Hydrogen.
NASA - National Aeronautics and Space Administration.
NEREL - National Renewable Energy Laboratory.
O&M - Operation and Maintenance.
PV - Photovoltaic.

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