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Original Research Article

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

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ABSTRACT

The threat to environmental sustainability due to greenhouse gas emissions from fossil fuels leads to the search for new energy sources, such as hydrogen, one of the most promising alternatives for use in the transport sector. Therefore, the main aim of this study is to evaluate the potential for producing hydrogen generated by electrolysis in plants along 3,187 km of highways in Brazil. A theoretical electrolysis plant powered by a photovoltaic system with a nominal power of 1.0 MW was simulated and evaluated in ten cities. Among the results, using the HOMER PRO software, the possibility of producing hydrogen in the range from 30.17 tons/year to 35.33 tons/year per installed MW stands out, at the Levelized Cost of Hydrogen in the range from 3.0 to 4.0 US$/kg of hydrogen. These results encourage continued research into the production and use of hydrogen in Brazil.

KEYWORDS

Green hydrogen, Electrolysis, Green energy, Hydrogen, Photovoltaic energy, HOMER PRO.

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INTRODUCTION

The growing increase in global energy demand and the use of fossil fuels worldwide increased greenhouse gas emissions, which are attributed to global warming and leading to climate change in some parts of the planet [1]. For this reason, several nations are together searching for new, less polluting, and renewable energy sources. Ensuring the generation of energy, considering environmental concerns, has become one of the greatest challenges of today [2].

Hydrogen production has gained prominence as an attractive alternative. Many researchers see it as the fuel of the future, mainly because it only releases water when burned in a fuel cell as an automotive fuel [3].

Among the green hydrogen production processes, photovoltaic or wind energy electrolysis is the most practical technical means to eliminate fossil fuels from the energy production cycle, especially when these energies come from the sun or the wind [4].

Integrating water electrolyzers and photovoltaic (PV) solar technology is a potential development in renewable energy systems, offering new avenues for sustainable energy generation and storage. This coupling uses PV-generated electricity DC to power electrolysis, breaking water molecules into hydrogen and oxygen. While oxygen produced can be delivered to the atmosphere, the produced hydrogen can be used as clean energy [5].

There are two ways to operate the electrolysis plant. It is possible to operate the electrolysis plant with or without battery storage. When solar energy is combined with batteries, excess solar energy may be stored for later use, maximizing energy efficiency and guaranteeing a steady supply of electricity even in the absence of direct sunlight. On the other hand, battery-free systems depend on the electrolyzer’s continuous power generation to convert solar energy into hydrogen during the day [5].

Electrolysis processing occurs in devices called electrolyzers. The three well-known types of electrolysis systems are alkaline electrolysis, proton exchange membrane (PEM), and solid oxide (SO) electrolysis [6]. However, alkaline and PEM electrolyzers are currently the technologies most used for hydrogen production via water splitting on a large scale [7].

Today, it is known that Brazil has one of the cleanest energy matrixes in the world, and that the North and Northeast regions of Brazil have a very high potential for clean energy, mainly from photovoltaic and wind energy, and that this potential varies from place to place [8].

Therefore, it is easy to understand that there are numerous possibilities for designing a hydrogen plant since there are at least three types of electrifiers and at least two types of energy sources. Despite this, this work has as its scope the evaluation of a photovoltaic green hydrogen plant which is the object this study and whose basic descriptions are described below.

This work fills at least four gaps: it quantifies the potential for green hydrogen production in two regions of the country, estimates the production costs of green hydrogen can be produced, and mobilizes the scientific community to research and publicize green hydrogen as an alternative form of energy for the transportation sector, explained above.

In Brazil, the first installations of photovoltaic power generation were mentioned in the BEN - National Energy Balance in 2011 as 1.0 MW, and since then, it has only grown. In 2015, it was already 21.0 MW. In 2020, it accumulated 3,297 MW. In 2021, the amount installed was 4,632 MW [9]. All this demonstrates that photovoltaic energy production is mature enough for a green hydrogen program in Brazil. But nobody knows the potential hydrogen amount that can be produced per year per MW of photovoltaic power in each place in Brazil. So, this is another gap to be filled by this work.

In Brazil, hydrogen gray is produced in oil refineries, using fossil fuels as raw material and energy input [10]. This results in hydrogen being at a low cost, between 1.0 U$$/kg and 1.5 U$$/kg [8]. Thus, from an economic point of view, green hydrogen has a low attractiveness. So, in terms of costs, there is still the challenge of making green hydrogen from renewable energy competitive compared to gray hydrogen, produced through steam reforming [8].

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Furthermore, distributed production of green hydrogen for the automotive sector is a new and little-known topic in practice, so little is known about production costs. Therefore, this is a gap to be filled by this work.

In this context, the reference plant is simulated and evaluated for the environmental conditions of the Brazilian cities of Belém, São Luís, Teresina, Fortaleza, Natal, João Pessoa, Recife, Maceio, Aracaju, and Salvador. HOMER PRO 3.14.5 is used to quantify the potential for production of electrical energy and hydrogen, and their respective levelized production costs.

Figure 1 shows in red the imagined route for the highway that connects ten capitals in the North and Northeast of Brazil, eight of which are in the semi-arid region of Brazil. The highway begins in Belém, the capital of the state of Pará, in the North, and ends in Salvador, capital of Bahia, in the Northeast, totaling 3,187 km. The legend on the right side of Figure 1 shows the daily solar irradiation in the region considered.

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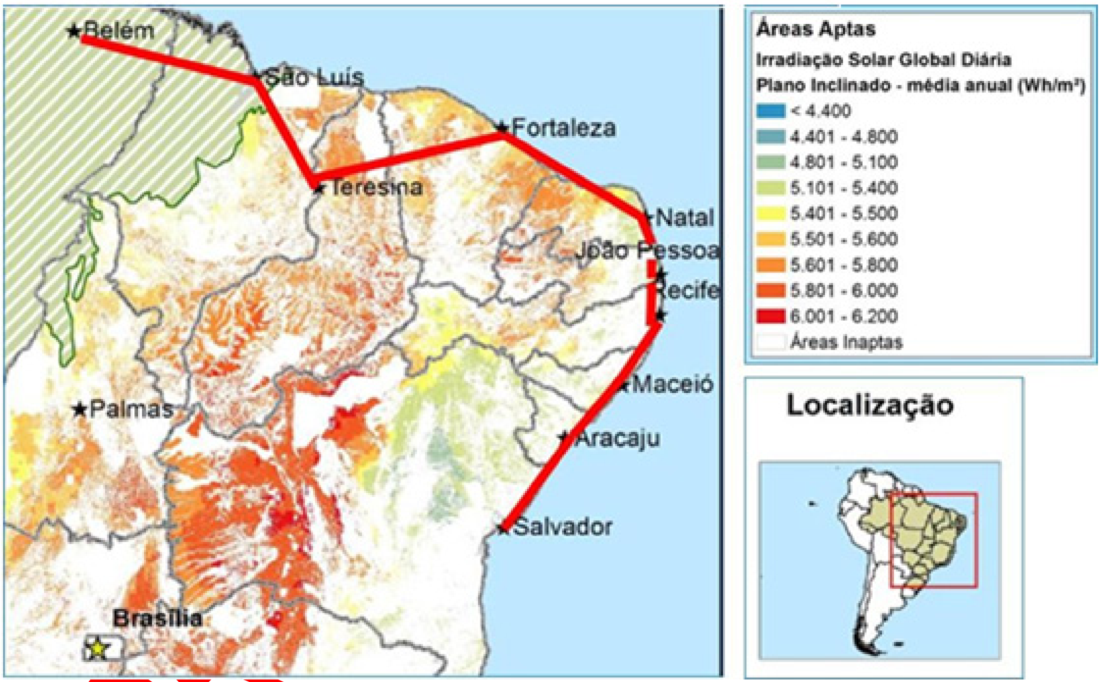

Figure 1. The highway object of this study (left side) and the daily solar irradiation (right side)[8]

The following reasons, described in [11], justify this work:

- Today, 50 years after the oil shock of the early 1970s, the world faces growing geopolitical tensions and uncertainty in the energy sector. There are parallels between then and now – oil supplies are in focus amid a crisis in the Middle East - but there are also differences: the global energy system has changed considerably.
- The crisis of the 1970s was about oil, but today's pressures come from many different areas. The world is now dealing with both oil and an acute climate crisis, with increasingly visible effects of climate change caused by fossil fuel use, including the record heatwaves experienced in the world in recent years.
- Today, we have clean energy technologies. The renewable energy technologies of solar and wind, solar and electric cars, electrolysis, electrolysis, electrolyzers, and fuel cells are all mature, well-established, and readily available.

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As previously stated, Brazil's solar potential is high and growing continuously, especially in the semi-arid region of the Northeast where the annual average of solar irradiation is around 6.03 kWh/m^2, which can bring contributions both at the regional level and on a broader scale [12].

Furthermore, the clean energy transition is gaining real and visible momentum. Whereas in the 1970s, many countries started from scratch as they struggled to respond to the oil shock, clean energy deployment is moving faster than many countries realize. And it can and must move even faster if the world is to meet the energy and climate goals shared by many nations. Furthermore, the international processes and agreements in place today, such as the Paris Agreement, provide a framework for strategic action to obtain results by the governments together [11].

To carry out the necessary simulations and evaluations, HOMER Pro was parameterized with the premises suggested by the International Energy Agency to the Group of Twenty (G-20), resulting in this work, which contains the following sections: a) this introduction, b) background, c) materials and methods, d) results, e) analysis and f) conclusions.

Finally, this work aims to contribute to the sustainability of the planet and the energy transition through this study of alternative sources and forms of clean energy that can replace fossil fuels in the transport sector.

BACKGROUND

The idea of using hydrogen as a fuel is not new. In the 18th century, hydrogen was used to design gas balloons, such as the Charlière hydrogen balloon in 1783. Ferdinand von Zeppelin used hydrogen, in a mixture with gasoline in propulsion technology, to fly Zeppelins in the 19th century [13].

In the 1970s, General Electric (GE) actively participated in project studies and research and development projects on the use of hydrogen in aircraft propulsion systems. NASA used the idea and contributed significantly and almost automatically using it in your National Aerospace Aircraft Program [14 - 15].

Likewise, 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. The American highway shows filling stations with a capacity between 100 and 180 kg/day of hydrogen and another with a capacity of 360 kg/day [15]. Thus, the Americans demonstrate the use of hydrogen for the automotive transport sector and test hydrogen production processes.

Hydrogen has many favorable attributes: it has a higher energy density than all fuels, can be stored, can be produced and used for efficient processes, it is renewable, it is clean, can be transported in pipelines and tanks, and can be produced at the point of delivery to the end consumer. Additionally, it is possible to industrialize on a large scale, and if used as fuel and burned in an internal combustion engine or a fuel cell, it emits zero greenhouse gases [16].

For all this, it is an excellent choice as an energy source for heating and electricity generation, among many others. As a result, it is considered the most environmentally friendly and promising energy source to replace fossil fuels in several sectors of the global economy.

The most abundant gas in the universe is hydrogen. It is colorless, odorless, tasteless, and constitutes approximately 75% of the universe’s mass. Regardless of the reality that hydrogen is abundant throughout the universe, it is not found naturally as a free element or gas. Furthermore, it persists naturally in compounds with several other chemical elements, like coal, methane, natural gas, biomass water, and others. Before hydrogen can be used as an energy source, it must be separated from its raw material [16]. Several materials can be used as raw material and/or energy in hydrogen production. Among the large-scale production processes, the following stand out: gasification, steam reforming, partial oxidation, and electrolysis [3]. As mentioned, this work is dedicated to the electrolysis process and the raw material is water.

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Global hydrogen production in 2023 was 97 Mt, predominantly dependent on fossil fuels, continuing the trend of recent years, and is expected to remain largely unchanged in 2024. The natural gas route accounted for around two-thirds of total production. Hydrogen production from coal gasification accounted for 20% of the global total. In addition, over 15% of hydrogen globally is produced as a by-product in refineries and the petrochemical industry, from processes such as naphtha reforming. Low-emission hydrogen production was less than 1% of global production. This low-emission hydrogen mainly relies on fossil fuel production with carbon capture. Green hydrogen production still represents only a small share of the total, remaining below 100 kt in 2023. China, Europe, and the United States account for around 75% of global green hydrogen production [11].

Photovoltaic green hydrogen, as studied in this work, is not yet produced on a large scale despite equipment with sufficiently mature technologies. This low penetration of green hydrogen is mainly due to production costs, which are still high compared to hydrogen produced with fossil fuels. However, the project pipeline shows that more than 400 GW of electrolysis to hydrogen will be operational by 2030.

A report presented in 2019 to the G20 (Group of Twenty) shows that it is possible to produce low-cost green hydrogen in the range of US$2.0 - US$4.0 per kilogram and that this depends on the solar and wind potential of the location where the plant will be installed and on some technical premises assumed for the project [17].

Hydrogen production costs from electrolysis depend on various technical and economic factors, such as a) CAPEX requirements, b) conversion efficiency, c) electricity costs, d) hours of operation most importantly, and e) capital costs [17].

Figure 2 shows the hydrogen production cost in US$/kg as a function of operating hours, keeping the discount rate at 8%, electricity cost fixed at 40 U$/MWh, and the five Levelized Cost of Hydrogen (LCOH) curves for five capital values versus operating hours, being a curve for electrolyzer capital costs in the range from $250\ \mathrm{US\$}/kWe$ to $650\ \mathrm{US\$}/kWe$. It is easy to see that the LCOH is from 2.0 US$ - 4.0 US$ per kilogram, starting from 2,000 hours of operation per year, as presented by the International Energy Agency (IEA) [17].

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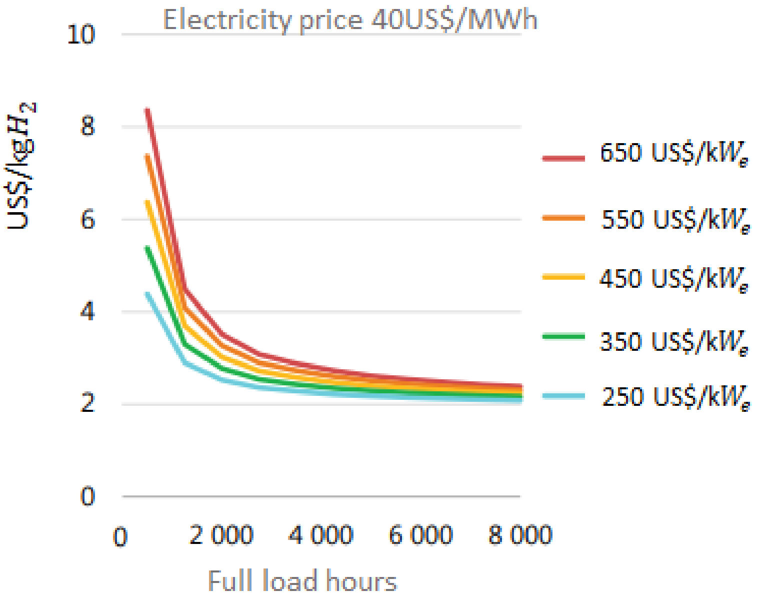

Figure 2. IEA hydrogen production costs projections [17]

Looking at Figure 2 is possible to conclude that [17]:

a) The LCOH decreases with increasing hours of electrolyzer operation.

b) The low cost of electricity and enough to ensure that the electrolyzer can operate at full load for a long time is essential to produce hydrogen at low cost.

c) In electrical systems with increasing shares of renewables, excess electricity can be available at low cost.

d) Running the electrolyzer at full load and using as much electricity as possible could decrease the LCOH.

Several other projects to produce hydrogen from dedicated renewable resources in various parts of the world are in development or have been announced by some countries. In areas where both resources are excellent, combining solar PV and onshore wind in a hybrid plant can lower costs further [17].

Figure 3, extracted from an IEA document, presents a qualitative map of green hydrogen costs considering: electrolyzer CAPEX = USD 450/k*We*, efficiency (LHV) = 74%; solar PV CAPEX and onshore wind CAPEX = between USD 400 - 1,000/kW and USD 900 - 2,500/kW depending on the region; discount rate = 8% [17].

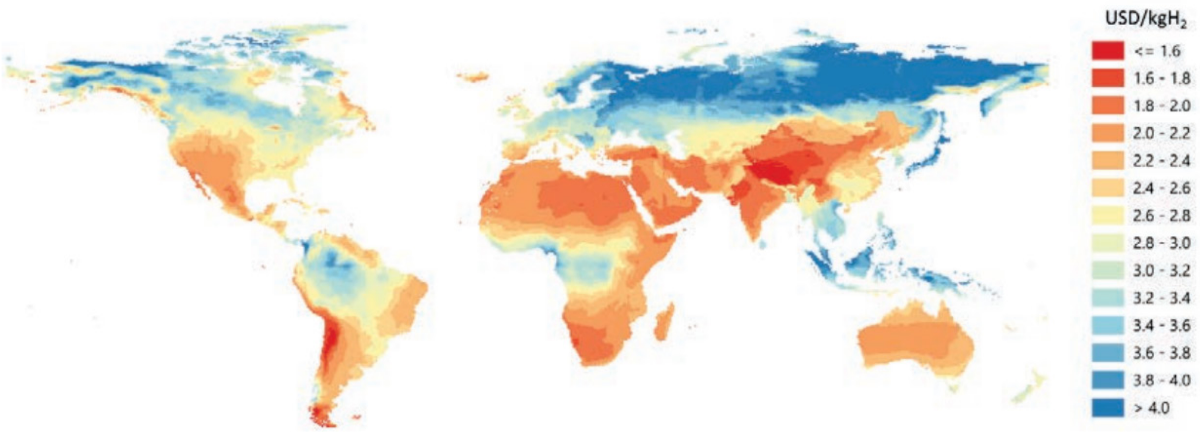

Figure 3. Green hydrogen costs [17]

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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 described before in the range from 2.0 US\$/kg - 4.0 US\$/kg, through electrolysis plants powered by photovoltaic energy of 1,000 kW, considering the following financial assumptions:

a) Electrolyzer capital cost of 450 US\$/*KWe*, the average of the IEA simulations [17],
b) Photovoltaic energy at 40 US\$/MWh, obtained in simulations with PV of 1,000 kW at a capital cost of 900 US\$/kW [19],
c) Discount rate of 8% per year [17],
d) Inflation of 3% per year [18],
e) Battery for energy storage costs 200 US\$/kWh capacity [8],
f) Sensitivity analysis of the capital cost of the electrolyzer for the values of 250 US\$/*kWe*, 350, US\$/*kWe*, 450 US\$/*kWe*, 550 US\$/*kWe* and 650 US\$/*kWe*, as it was performed by the IEA [17].

The plant subject to this study

In Figure 4 is presented the plant subject to this study; it is an autonomous, off-grid plant, consisting of an electrolyzer with 760 kW of hydrogen output, powered by a 1.0 MW photovoltaic system, whose hydrogen produced is clean and dry, and stored in a tank with a nominal capacity of 100 kg.

The plant also contains a battery bank and a charge controller to store excess electricity generated by the photovoltaic system to be used during low solar irradiation.

The choice of a plant with the characteristics shown and described above is because this work is a small part of a study carried out over three years to evaluate the potential for photovoltaic green hydrogen production considering the Brazilian solar potential. Other characteristics will be described in the section that deals with the premises and assumptions.

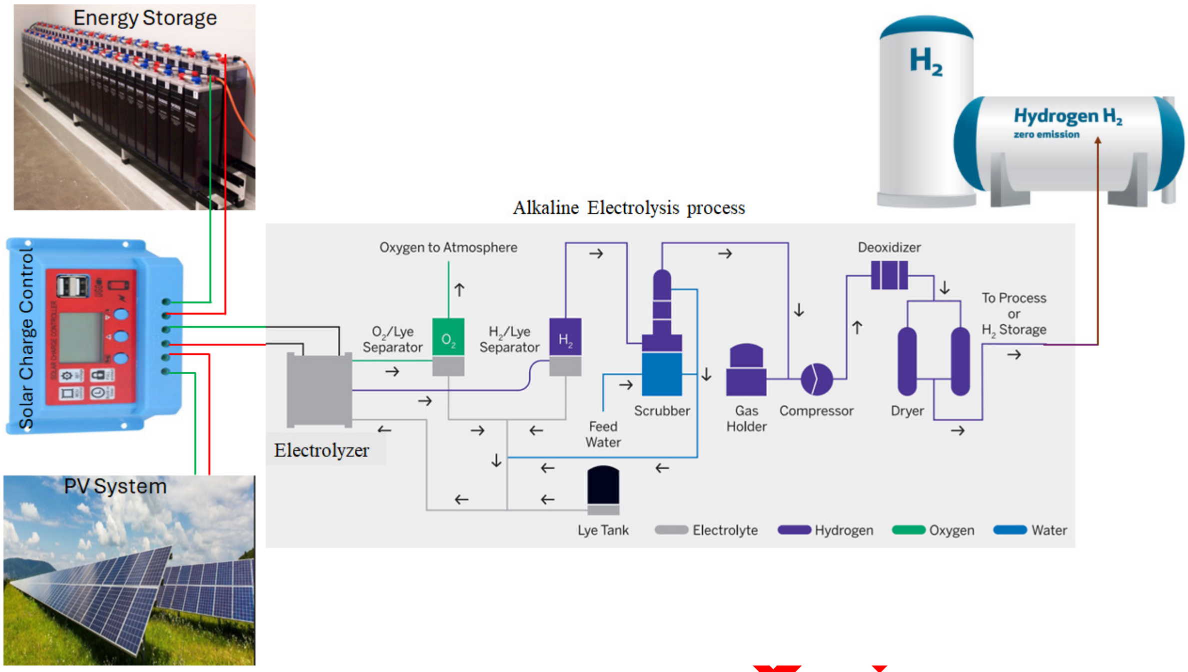

Figure 4. The Photovoltaic hydrogen plant object of this study

Project and constraints assumptions and design assumptions

This work aims to simulate a green hydrogen photovoltaic plant. Thus, all the energy used in the process comes from a solar energy source, and being solar, half of the year is in operation (during the day) and half of the year is black-out (without power at night).

Therefore, the design assumptions are the constraints shown in Table 1 and the design assumptions shown in Table 2.

Table 1. Constraints assumptions

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

Table 2. Design assumptions

Data name	Unit	Value	Source
Discount rate	%	8.0	[17]
Inflation rate	%	3.0	[18]
Annual capacity shortage	%	50	[19]
Project lifetime	Years	25	[17]

Technical data and assumption of photovoltaic system

Among numerous commercial in Brazil or imported mainly from China, solar energy is readily accessible for producing electricity in off-grid systems. In the simulations carried out in

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this work, the generic photovoltaic system alternative offered by the HOMER PRO library [20] and the specifications and restrictions shown in Table 3 were used.

Table 3. Assumptions for photovoltaic system

Data name	**Unit**	**Value**	**Source**
Capital Costs	US$/kW	900	[19]
Replacement Costs	US$/kW	900	[19]
O&M Costs	US$/year	9.00	[19]
Efficiency	%	16.4	[20]
Lifetime	Years	25	[15]
Derating Factor	%	96	[20]
Rated Capacity	MW	1.0	[20]

Technical data and assumption of electrolyzer

HOMER PRO does not have a database with the technical specifications of commercial electrolyzers available on the market. Thus, a generic electrolyzer with an input-rated capacity of 1,0 MW will be used. The assumptions adopted for the electrolyzer in this study are presented in Table 4.

Table 4. Data assumptions for generic electrolyzer

Data name assumption (Constraints)	**Unit**	**Value**	**Source**
Power output	kW	760	[19]
Efficiency	%	76	[8 - 18]
Lifetime	Years	15	[17]
Capital Costs	US$/kW	450	[17]
Replacement Costs	US$/kW	450	[17]
O&M Costs	%/year	1%	[19]

Technical data and assumption of battery 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 loaded into the computational code and 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 [20]. In addition, for the battery bank used in this work, the assumptions and constraints shown in Table 5 were adopted and configured in HOMER PRO.

Technical data and assumption of hydrogen storage tank

Regarding hydrogen storage, two situations were considered: a) using a tank with a capacity of 50,000 kg to quantify annual production, and b) a service tank with a capacity of 100 kg when in continuous operation to estimate LCOH with autonomy of one day.

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Table 5. Batteries specifications

Data name assumption (Constraints)	Unit	Value	Source
String size	-	20	[19]
Voltage	V	220	[19]
Initial State of Charge	%	100	[19]
Minimum State of Charge	%	20	[19]
Throughput	kWh	100	[19]
Lifetime	year	4	[20]
Capital Costs (average)	US$/Unit.	200	[17]
Replacement Costs	US$/Unit.	200	[17]
O&M Costs	US$/kW/year	2	[17]

METHOD AND MATERIAL

This section describes the method adopted and presents the research material and the HOMER Pro tool used in the work.

The tool HOMER PRO

In recent years, many technical and economic studies have been conducted on using hybrid renewable energy resources.

The Hybrid Optimization of Multiple Energy Resources (HOMER) modelling tools has emerged as one of the best and most popular tools globally [16 - 17] after effective use in their research on renewable energy system design, optimization, and analysis tools.

The HOMER PRO Micro Power Optimization Model is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist micropower systems design and to facilitates the comparison of power generation technologies across a wide range of applications [12].

It performs the main tasks: simulations, optimization, and sensitivity analysis.

In the simulation process, HOMER PRO models the 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 system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost and determines the optimal value of the variables over which the system has control, such as the mix of components that make up the system and the size or quantity of each [12].

Sensitivity analysis conducts multiple optimizations with varying input assumptions to assess the impact of uncertainty or changes in model inputs [12].

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 [12].

For all these reasons, this work uses HOMER PRO 3.14.5 as a tool to perform the optimizations, simulations, and sensitivity analyses necessary to answer the questions of this research.

In the Figure 5 is presented a schematic of the simulated system using the HOMER with de electrolyse, batteries and all other parts of the plant.

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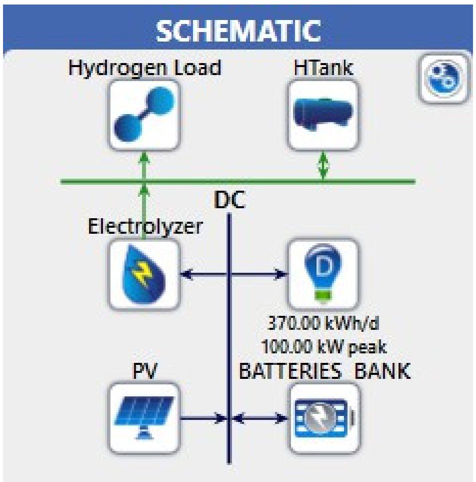

Figure 5. HOMER design of the plant

Method

The approach followed in this research is demonstrated in the flowchart represented in Figure 6, which objectively shows how HOMER PRO is parameterized to be used to execute the simulations proposed in this work. It is used to fetch data from the environmental conditions of the ten locations in studies and simulates the electric energy and the amount of hydrogen possible to be produced in each of them and their respective levelized cost, 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.

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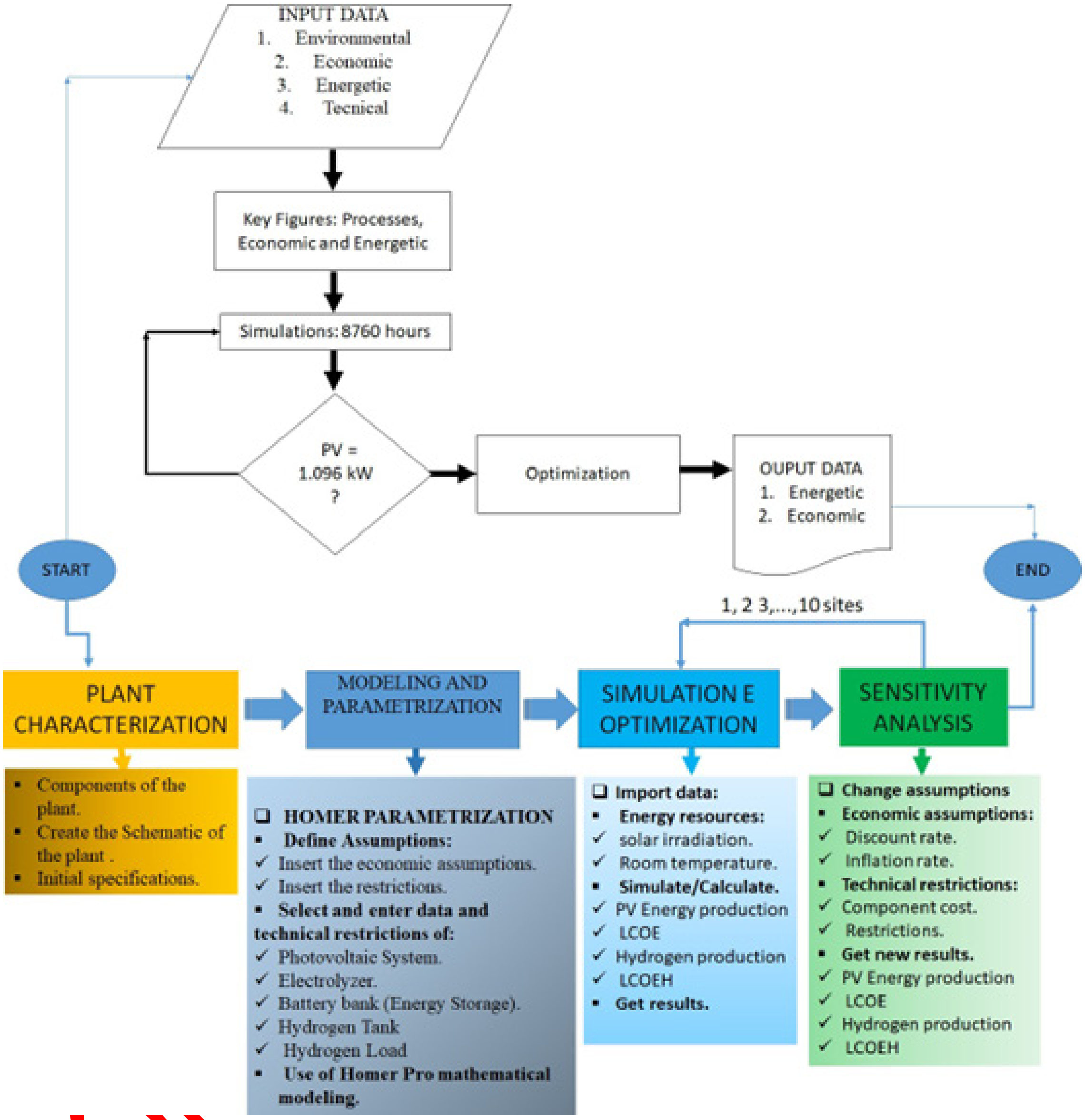

Figure 6. Flowchart of dynamic simulation and optimization

Simulation and optimization

After completing all the steps detailed in Figure 6, the HOMER PRO is ready for use. The next step is to download solar irradiance and temperature data from NASA's database for each place along the highway.

Plant simulations and optimizations are performed considering the environmental conditions of each location along the highway, using HOMER PRO's algorithm and mathematical modeling, according to the following equations.

Calculation of the PV array output

The Solar Homepage GHI Resource allows you to quantify the global horizontal radiation (GHI) to simulate the output power of a PV array. The GHI is the total amount of solar radiation reaching the horizontal surface of the Earth, which HOMER PRO uses to calculate the global solar radiation incident on the surface of the PV array. It uses eq. (1) to calculate the output power of the array [20 - 21]:

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

Where:
Y_{PV}: 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. At night, it is the same as the ambient temperature, but in the full sun, the cell temperature can exceed the ambient temperature by 30°C or more [20 - 21].
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. Otherwise, it assumes that the temperature coefficient of power is zero, so the eq. (1) is simplified to eq. (2) [20 - 21]:

$$P_{PV} = Y_{PV}\, f_{PV}\, (G_T / G_{T,STC}) \tag{2}$$

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 eq. (3) [20 - 21]:

$$E_{PVout} = \int_0^{t1} P_{PV}\, dt + \int_{t1}^{t2} P_{PV}\, dt + \ldots + \int_{tn-1}^{8760} P_{PV}\, dt \tag{3}$$

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 eq. (4) [20 - 21]:

$$LCOE = (C_{ann,tot} - C_{boiler}.H_{served})/E_{served} \tag{4}$$

where:
$C_{ann,}$: total annualized cost of the system [US$/yr].
C_{boiler}: boiler marginal cost [US$/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 only, PV is used and do not serve a thermal load ($H_{thermal}$=0), this term is zero, and LCOE is calculated using eq. (5) [20 - 21].

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

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 eq. (6) [20 - 21]:

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

where:
$C_{NPC,\ tot}$: total net present cost [US$].
i = annual real discount rate [%].
R_{proj}= project lifetime [year].
CRC = a function returning the capital recovery factor.

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Hydrogen produced

The HOMER PRO calculates hydrogen production by electrolyzer efficiency, that is the efficiency with which the electrolyzer 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 [20 - 21].

LCOH - Levelized Cost of Hydrogen

HOMER PRO uses eq. (7) to calculate the LCOH - Levelized Cost of Hydrogen [20 - 21].

$$LCOH = [C_{ann,tot} - V_E(E_{p,AC} + E_{p,DC} + E_d + E_g)]/M_H \tag{7}$$

where:
$C_{ann,\ tot:\ total}$: annualized cost of the system [US$/year]
V_E: electric energy cost value [US$/kWh]
$E_{p,\ AC}$: primary AC energy load [kWh/year]
$E_{p,\ DC}$: primary DC electrical load served [kWh/year]
E_d: deferrable energy [kWh/year]
E_{gr}: energy from grid [kWh/year]
M_H: mass of hydrogen produces [kg]

In this case, the energy served to the hydrogen plant is produced by its own photovoltaic system. Therefore, the second term of the numerator is zero, and the LCOH is calculated using eq. (8) [20 - 21].

$$LCOH = C_{ann,tot}/M_H \tag{8}$$

Costs 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, 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. So, it was decided, for reasons of objectivity, to obtain results and sensitivity analysis only at the capital cost of the Electrolyzer. So, the sensitivity analysis of the capital cost of the electrolyzer for the values of 250 US$/$kWe$, 350, US$/kWe, 450 US$/$kWe$, 550 US$/kWe and 650 US$/$kWe$, as it was performed by the IEA [7-9].

Research material

The material for this research is the data on Monthly Average Global Solar Irradiance and Monthly Average Temperature for each location, which HOMER PRO downloads from the NASA database and then converts into electrical energy, which is then converted into hydrogen through the electrolysis process, using the algorithm and mathematical modelling of its computer code.

Table 6 presents data relating to solar irradiation and temperature in each location, which are the input data for HOMER Pro to estimate photovoltaic energy generation in each location.

Table 6. Energy resources

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′ S; 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

RESULTS

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

Amount of produced energy and costs at each site

Table 7 shows, in the first column, the name of each site where the power plant was simulated. The second column shows the latitude and longitude of each location. The third and fourth columns show the amount of energy produced per year and the respective levelized cost of production.

Table 7. The energy produced and LCOE on each location

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

Table 8 shows the results of the simulations performed to analyze the sensitivity of the cost

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of hydrogen produced to the capital cost of the electrolysis plant. The first column shows the name of each location. The second column shows the amount of hydrogen produced per year. The other columns show the levelized costs of hydrogen produced as a function of the capital cost of the electrolyzer, from US\$650/kW, US\$550/kW, US\$450/kW, US\$350/kW to US\$250/kW of installed capacity, respectively.

Table 8. Hydrogen produced and LCOH

		LCOH	LCOH	LCOH	LCOH	LCOH
Capital Costs	Production	650(*)	550(*)	450(*)	350(*)	250(*)
City	ton/year	US\$/kg	US\$/kg	US\$/kg	US\$/kg	US\$/kg
Belém	30.48	4.94	4.59	4.24	3.90	3.55
São Luís	30.17	4.94	4.59	4.24	3.90	3.55
Teresina	34.37	4.34	4.03	3.72	3.41	3.11
Fortaleza	34.45	4.33	4.02	3.72	3.41	3.10
Natal	34.51	4.32	4.02	3.71	3.40	3.09
João Pessoa	32.97	4.53	4.20	3.88	3.56	3.24
Recife	35.33	4.16	3.86	3.56	3.26	2.95
Maceio	32.40	4.64	4.31	3.98	3.66	3.33
Aracaju	32.57	4.58	4.26	3.93	3.60	3.28
Salvador	30.19	4.88	4.53	4.17	3.82	3.47

(*) US\$/kW output of electrolyzer.

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

Table 9. PV and Electrolyzer operating time

Site	PV	Electrolyser
City	hours/year	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

Since the Photovoltaic system operates longer than the Electrolyzer, there is excess electricity. This excess is shown in Table 10.

Electricity Excess

Table 10 shows that in Teresina excess energy is greatest with an amount of 199.50 MWh/year. The lowest excess energy occurs in Belem, where the excess energy is only 119.27

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MWh.

Table 10. Electricity excess

Site City	Excess Energy MWh/year
Belém	119.27
São Luís	150.77
Teresina	199.50
Fortaleza	157.77
Natal	194.79
João Pessoa	178.46
Recife	185.64
Maceio	182.45
Aracaju	177.62
Salvador	141.32

Levelized costs with battery bank

HOMER PRO simulated the plant performance with and without battery banks in the ten locations evaluated, finding that the use of battery banks increases the cost of hydrogen production excessively. Table 11 shows the results obtained for the plant evaluated near Recife, where the best results were obtained.

Table 11. LCOH with battery bank

Batteries Quantity	LCOH US$/kg	Comparison
0	3.65	1.00
20	3.82	1.05
60	4.35	1.19
100	4.88	1.34
200	6.12	1.68
220	6.19	1.70
420	7.95	2.18
840	8.03	2.20

ANALYSIS

This section of the work aims to analyses the data obtained in the simulations performed by HOMER PRO to obtain answers to the questions of the researchers and concludes the work.

Amount of produced energy analysis

Figure 7 compares the amount of electricity produced in each place per year. It also shows that Recife has the highest production, with 2,195 MWh/year per MW installed, which occupies the first position in the Ranking. The one with the lowest production is Belém, with 1,849 MWh, which occupies the tenth position. The average potential along the highway studied is 2,024 MWh/year per MW installed.

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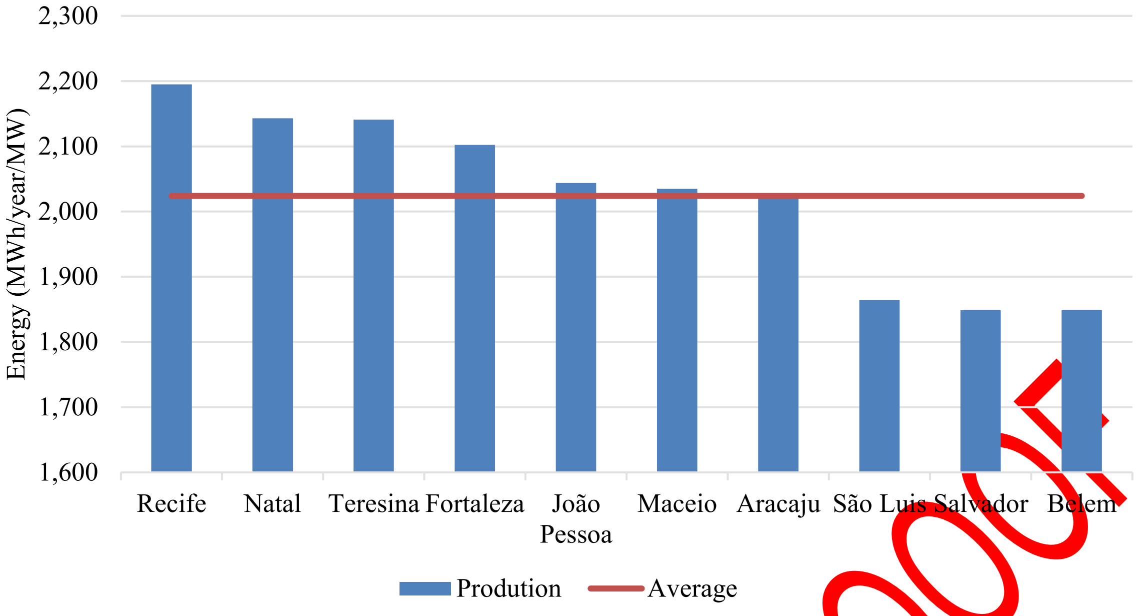

Figure 7. The Ranking of the total amount of energy produced in each place

Figure 7 also shows that the energy production potential of the cities located in the Northeast Region is above the average, while the potential of Belem, which is in the North is below the average.

Energy Coste analysis

Figure 8 compares the levelized costs of electricity produced in each place per year. It also shows that Recife has the lowest levelized production costs, with 34.9 USS/MWh and occupies the first position in the Ranking. The one with the highest levelized productions costs is Belém, with 43.4 US$/MWh, which occupies the tenth position. The average potential along the highway studied is 39.20 US$/MWh.

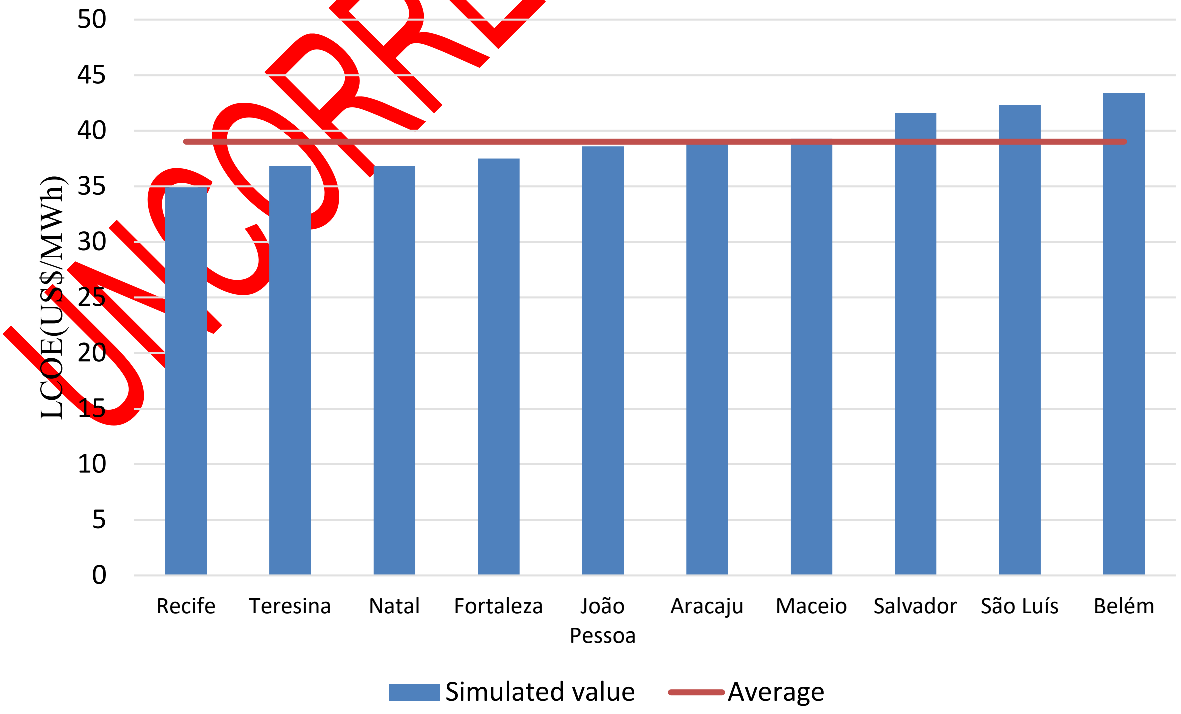

Figure 8. Levelized Energy Costs (LCOE)

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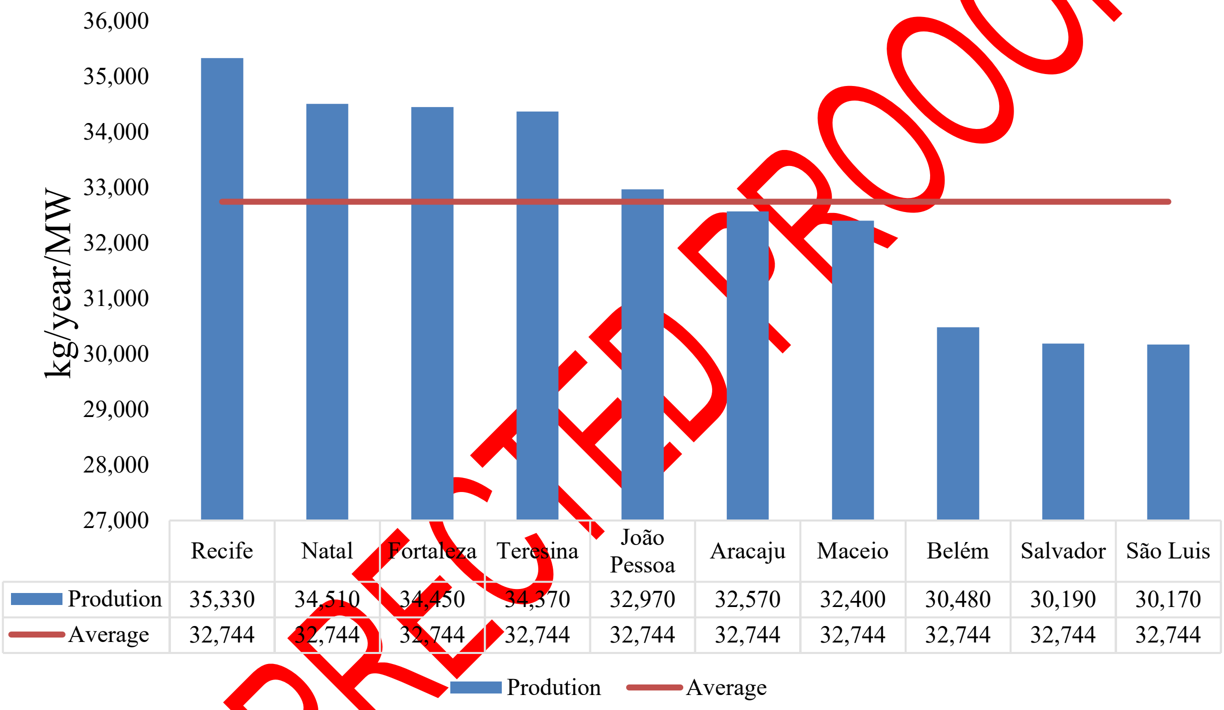
The production of electricity at an average cost of US$39.20/MWh corroborates the estimates made by the International Energy Agency that it is possible to produce green energy at a cost of US$40.00/MWh.

Hydrogen production analysis

Figure 9 shows the Ranking according to the hydrogen production potential of each city evaluated along the highway that connects the North and Northeast of Brazil. Figure 9 shows that Recife has the potential to produce 35.33 tons/year of hydrogen for each MW of installed energy, thus occupying the first position in the Ranking. Natal and Fortaleza have the potential to produce 34.51 tons/year and 34.45 tons/year, respectively. The site with the lowest production potential and last in the Ranking is São Luis, able to produce 30.17 tons/year of hydrogen per MW.



	Recife	Natal	Fortaleza	Teresina	João Pessoa	Aracaju	Maceio	Belém	Salvador	São Luis
Prodution	35,330	34,510	34,450	34,370	32,970	32,570	32,400	30,480	30,190	30,170
Average	32,744	32,744	32,744	32,744	32,744	32,744	32,744	32,744	32,744	32,744

Figure 9. The Ranking of the total amount of energy produced in each place

So, Figure 9 shows that it is possible to conclude that the potential for hydrogen production along the highway under study is from 35.33 to 30.17 tons/year/MW with an average of 32.73 tons/year per MW installed.

Hydrogen production costs analysis

Figure 10 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 Electrolyzer. On the X axis is possible verify the LCOH; on the Y axis the location and the lines represent the LCOH for the different values of the electrolyzer capital cost.

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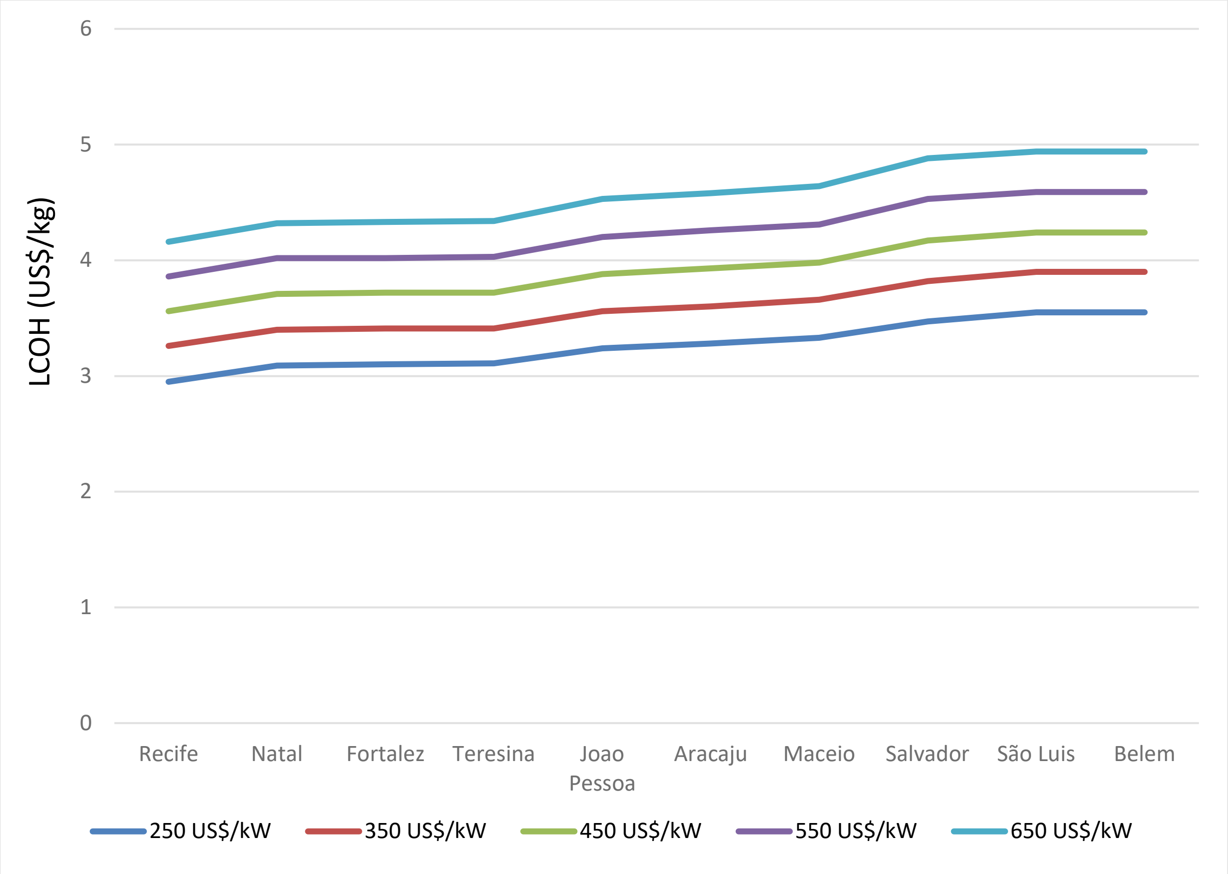

Figure 10. Analysis of sensitivity of LCOH to the cost of the electrolyser

Figure 10 shows that the cost of hydrogen production increases proportionally to the capital costs of the electrolysis equipment. At the capital cost of the electrolysis equipment of 250 US$/kW, it will be possible to produce hydrogen with LCOH in the range of 2.95 to 3.55 US$/kg. While at 650 US$/kW, it will be possible to produce hydrogen with LCOH in the range of 4.16 to 4.94 US$/kg in Recife and Belém, respectively.

Effect of battery use on levelized costs

Figure 11 shows the effect of the number of batteries on the levelized cost of hydrogen produced. It shows that production costs increase sharply with the installation of batteries, from US$3.65/kg in the condition without batteries to US$8.30/kg with 800 batteries installed, increasing the cost by one hundred and twenty percent.

So, all this allows us to conclude that the use of batteries increases the cost of hydrogen production, further reducing the attractiveness of green hydrogen.

On the other hand, not using batteries has operational effects on the plant's operation since the plant does not operate at night due to lack of energy, as shown in Table 9. It is a problem that still needs to be studied and solved.

The LCOH behavior in plant simulations at other locations mirrored that in Recife. Therefore, it is possible to conclude that, from an economic point of view, the use of batteries in green hydrogen photovoltaic plants contributes to reducing the attractiveness of projects of this type of plant.

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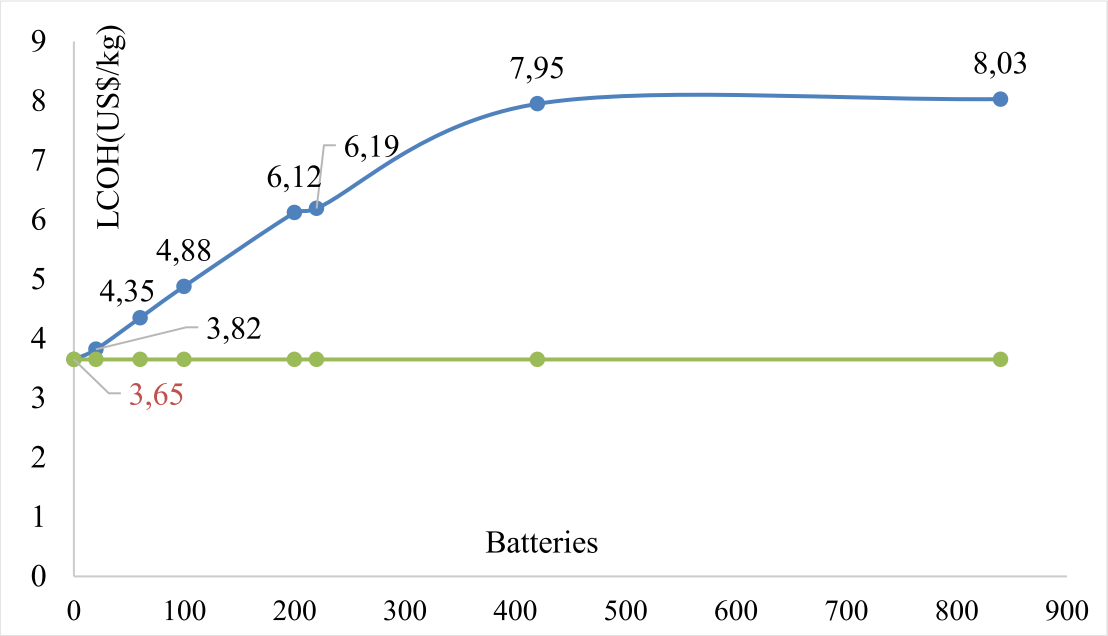

Figure 11. Effect of batteries on LCOH

On the other hand, not using batteries brings undesirable operational effects to the plant's operation since the plant does not operate at night due to lack of energy, resulting in less than 4000 hours of operation per year, as it was shown in Table 9.

CONCLUSIONS

This work fulfilled the initially planned scope, simulating and evaluating a 1.0 MW electrolysis plant powered by photovoltaic energy for the environmental conditions of ten locations interconnected by highways that connect the North to the Northeast of Brazil.

This work aimed to simulate the electrolysis plant that is the object of this study, considering the IEA studies, the boundary conditions, the premises, the restrictions, and the solar irradiation conditions of the ten selected cities, and concluded that:

a) It is possible to produce a lot of electricity along the highways that connect the North to the Northeast of Brazil in the range of 1,849 MWh in Belém and 2,195 MWh in Recife.
b) It is also possible to produce energy at a cost of 40$/MWh - IEA assumption. The simulations carried out here, allow us to conclude that it is possible to produce energy in the range of 34.9 US$/MWh in Recife and 43.40 U$/MWh in Belém, an average of 39.20 U$/MWh and median of 38.80 US$/MWh in Teresina.
c) It is possible to produce a lot of 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 30.17 ton/year in São Luis and 35.33 ton/year in Recife was obtained.
d) The initial hypothesis that LCOH along the road subject to this study would be in the range of US$3.0/kg to US$4.0/kg is fully valid only for electrolyzer costs lower than 350 US$/kW.
e) It is also possible to conclude that the use of batteries to store electrical energy greatly increases the cost of hydrogen production, causing hydrogen to lose its attractiveness. This results in a plant with a low load factor, as the plant can only operate during the day.

HOMER PRO proved to be an excellent tool for simulating the green hydrogen plant that is the subject of this study, but it was limited in terms of design development and detailing. The modelling does not include determining how many modules and photovoltaic cells are unnecessary and how they are associated in series or parallel. The same deficiency appears with the arrangements of the electrolytic cells

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Finally, this work recommends that the hydrogen production potential of each location subject to this study be evaluated considering the supply of wind energy and hybrid wind and photovoltaic, as a solution to increase the plant's load factor.

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NOMENCLATURE

Abbreviations

AC	Alternating Current
BEN	National Energy Balance
CAPEX	Capital Expenditure
DC	Direct Current
DNI	Direct Normal Irradiance
G20	Group of Twenty
GHI	Horizontal Global Irradiation
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
MG	Minas Gerais (Brazilian State)
NASA	National Aeronautics and Space Administration
NEREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PV	Photovoltaic
USD	United States Dollar

Symbols

A_{PV}	Surface area of the PV module	[m^2]
a_P	Cell temperature coefficient of power	[%/°C]
$C_{ann,\,tot}$	Total annualized cost of the system	[U$/year]
C_{boiler}	Boiler marginal cost	[$/kWh]
$C_{NPC,\,tot}$	Total net present cost	[U$]
E_d	Deferrable energy	[kWh/year]
$E_{p\mathrm{Ep,\,AC}}$	Primary AC energy load	[kWh/year]
$E_{p,\,DC}$	Primary DC electrical load served	[kWh/year]
E_{gr}	Energy from grid	[kWh/year]
E_{served}	Total electrical load served	[kWh/year]
f_{PV}	Derating factor	[%]
G_T	Solar radiation incident on the PV in the current time step	[kW/m^2]
$G_{T,\,STC}$	Incident radiation at standard test conditions	[1.0 kW/m^2]
H_{served}	Total thermal load served	[kWh/year]

i	Annual real discount rate	[%]
Y_{PV}	Rated power output of the PV module under standard test conditions	[kW]
$\eta_{mp,STC}$	Efficiency of the PV module under standard test conditions	[%]
R_{proj}	Project lifetime	[year]
T_{C}	PV cell temperature in the current time step	[°C]
$T_{C,STC}$	PV temperature under the standard test conditions	[25°C]
V_{E}	Electric energy cost value	[$/kWh]

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