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Simulation and Evaluation of a Large Scale Electrolysis Plant - A Case Study in a Brazilian Port

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ABSTRACT

Researchers from several nations think that hydrogen produced from electrolysis powered by renewable sources is the fuel of the future for the automotive sector. Previous work has shown that an off-grid electrolysis plant powered by photovoltaics (PV) is the most attractive alternative for Brazil considering multiple criteria. This work aimed to simulate and evaluate the performance of a water electrolysis plant located in Porto do Pecem, in the State of Ceará, in the Northeast Region of Brazil with Latitude: 3°;33.1'S and Longitude: 38°;49, 9'W. The HOMER PRO optimization software was used to design, optimize, simulate and evaluate an off-grid centralized hydrogen plant powered under three conditions: a) powered by photovoltaic energy; b) powered by wind energy; and c) powered by hybrid photovoltaic and wind energy. Currently, the Port of Pecém operates on natural gas receiving station that feeds three thermoelectric power plants, which in the future could be used as an export port for hydrogen produced by electrolysis of water with renewable energy. In Pecem, the average solar irradiation is 5.84 kWh/m²/day, and there is a considerable wind potential in this location with an average wind speed of around 6.87 m/s. This plant could be used as a reference for future studies in an eventual hydrogen program in Brazil. In the end, this work presents the amount of energy and hydrogen produced per year for plants with 1.35 GW of installed electrical power and conclude: a) It is possible to produce a lot energy and hydrogen in Pecem at a cost lower than 40.0 U$/MWh, b) It is possible to produce hydrogen with a cost in the range of 2.0 to 4.0 U$/ kg; and these results are in line with studies by the IEA - Energy International Agency.

KEYWORDS

Hydrogen, Electrolysis, Green Hydrogen, Photovoltaic Electrolysis, Wind, Electrolysis, Hydrogen Plant.

INTRODUCTION

Nowadays, energy consumption is rising rapidly due to industrialization and progress in the standards of living [1]. Global use of fossil fuels has increased along with world economic growth since the beginning of the Industrial Revolution in the 18th century: reversing this growth trend and continuing to expand the global economy will be a pivotal moment in the history of energy. The share of fossil fuels in the global energy mix has been stubbornly high, around 80%, for decades. As a result, the peak for global energy-related CO_2 emissions will be reached in 2025 at 37 billion tonnes (Gt) per year. This would be associated with an increase of around 2.5°C in global average temperatures by 2100 [2].

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Furthermore, reserves of fossil energy resources are finite and world oil reserves are confined to reserves concentrated in specific regions of the world. At the current rate of fossil consumption, reserves are expected to be depleted in less than 50 years [3].
The global transport sector consumes a quarter of total final energy consumption today and is responsible for nearly 40% of the emissions from end-use sectors. Oil dominates in transport, accounting for 90% of consumption. From 2010 to 2019, increasing demand for passenger and goods mobility resulted in the transport sector seeing the largest growth in emissions of all end-use sectors. In 2021, the global amount of CO_2 emissions from the sector it was of 7.7 Gt CO_2 [2]. Therefore, researchers from several nations think that hydrogen produced from electrolysis powered by renewable sources is the fuel of the future for the automotive sector. Hydrogen fuel cells is considered as a promising technology for future global energy supply [1]. All of this justifies studying hydrogen, a clean fuel, which when produced from water and with renewable energies, and used as fuel for fuel cells, only produces electricity and water.

Hydrogen option

The use of hydrogen together with hydrogen fuel cell together two technologies that are considered a promising technology for the future global energy supply [1], in this case, hydrogen would be used as an energy input together with a fuel cell to move vehicles, trains, trucks, planes in the transport sector; in fixed power generation plants and as a power source for electronic devices. However, hydrogen has other uses. It can be used in the domestic sector as an energy input for heating and cooking; it can be used as an energy input for heating processes as a fuel for industrial processes; in the petrochemical industry to enrich fuels; in the chemical industry in the production of ammonia for the agricultural sector, among other applications [4-5].
In addition, hydrogen is easy to produce using various products as feedstock and energy input. Current global production is 70 million tons per year, 76% of which is produced from natural gas by the SRM - Steam Metane Reform process, 22% through coal gasification and 2% through electrolysis [4].
In large SMR plants and small scale, SMR, the raw material cost, which is NG - Natural Gas, contributes with around 52 to 68% of the final price of hydrogen. The remainder is mainly composed of capital charges [1]. Problems with the SMR process are that it depletes energy and produces CO_2. To give you an idea, a plant with a capacity of one million cubic meters per day of hydrogen emits about 0.3-0.4 million standard cubic meters of CO_2 into the atmosphere daily. So, if necessary, add a gas cleaning and CO_2 capture and storage unit (CCS), which adds approximately 25-30% additional cost for hydrogen production [6].
The coal gasification processes occur in equipment called gasifiers, and can be described by a set of processes and chemical reactions that occur in different regions of the gasifier or simultaneously throughout its entire volume. In a simplistic way, it is possible to say that the first process consists of drying to eliminate moisture, followed by the pyrolysis process, carbon oxidation, gasification itself, tar cracking, partial oxidation of the pyrolysis products, which in the end results in a mixture of gases commonly called Syngas containing H_2 , CO, CO_2, CH_4, and H_2O; in cases where the raw material is coal, sulfur (S) is contained in the Syngas that is produced [7]. Therefore, the gasification plant needs a CO_2 capture and storage unit (CCS), and this causes the purity of hydrogen produced from coal to rise from 20% to 95%, and the purity of hydrogen produced from gasification of biomass rises from 40% to 95% [8].

Electrolysis processes

The electrolysis of water is an electrochemical process that takes place in a device called an electrolyser, in which electrical energy is the driving force of chemical reactions. The process

basically consists of applying a potential difference in direct current between the electrodes inserted in a solution of water and an electrolyte, circulating an also continuous electric current between them, splitting the water molecule. In the process, hydrogen ions, which are positively charged, migrate to the negatively charged cathode, where they are reduced to form hydrogen gas (H_2). The oxygen ions that are negatively charged, migrate to the anode that is positively charged, where they are oxidized to form oxygen gas (O_2). A ceramic separator or microporous material placed between the anode and cathode separates hydrogen from oxygen. The passage of electric current through small potential differences is facilitated by reducing the electrical resistance of the cell, with the use of electrolytes, which facilitates the transport of ions necessary for the process [9].
As shown in Figure 1, there are four types of electrolyser: a) AEC (Alkaline Electrolyser); b) PEM (Proton Exchance Membrane Electrolyser); C) AEM (Anion Exchange Membrane Electrolyser) and d) SOEC (Solid Oxid Electrolyser) [10].

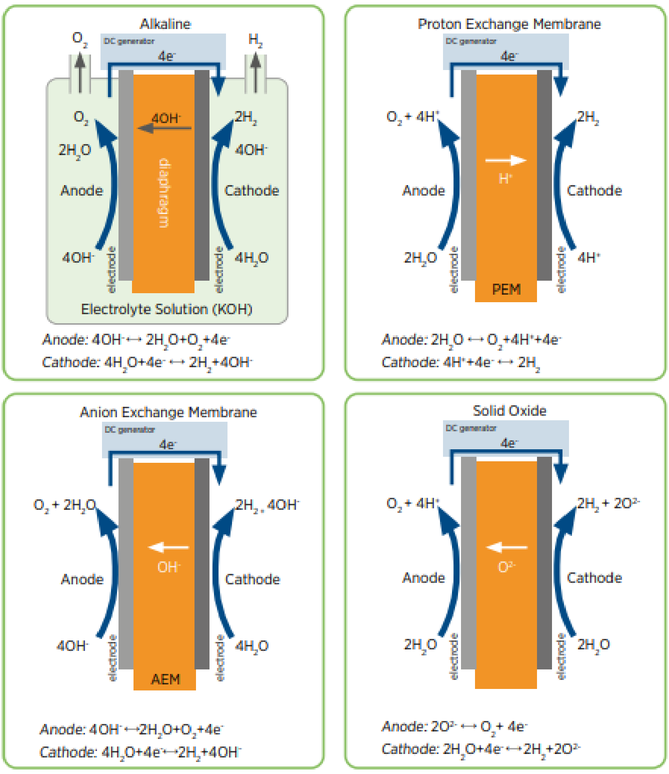

Figure 1. Electrolysis technologies [10]

The state of the art and future KPIs (Key Performance Indicators) for electrolyser technologies for large-scale hydrogen production plants, are shown in Figure 2.
The state of the art of the first two technologies, the AEC and the PEM seems ready to support a large production program, as they are mature technologies, with a nominal capacity of around 1.0 MW per unit, with a conversion rate of energy into hydrogen in the range of from 42 to 66 kWh/kg of hydrogen, with a purity greater than 99.99% and a useful life greater than 50,000 hours of operation; with estimates that by the year 2050, these electrolysers will be manufactured with a power greater than 10 MW per unit [10].

	2020	Target 2050	2020	Target 2050
	PEM electrolysers		Alkaline electrolysers	
Nominal current density	1-2 A/cm²	4-6 A/cm2	0.2-0.8 A/cm²	> 2 A/cm²
Voltage range (limits)	1.4-2.5 V	< 1.7 V	1.4-3 V	< 1.7 V
Operating temperature	50-80°C	80°C	70-90°C	> 90°C
Cell pressure	< 30 bar	> 70 bar	< 30 bar	> 70 bar
Load range	5%-120%	5%-300%	15%-100%	5%-300%
H_2 purity	99.9%-99.9999%	Same	99.9%-99.9998%	> 99.9999%
Voltage efficiency (LHV)	50%-68%	>80%	50%-68%	> 70%
Electrical efficiency (stack)	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2
Electrical efficiency (system)	50-83 kWh/Kg H_2	< 45 kWh/Kg H_2	50-78 kWh/Kg H_2	< 45 kWh/Kg H_2
Lifetime (stack)	50 000-80 000 hours	100 000-120 000 hours	60 000 hours	100 000 hours
Stack unit size	1 MW	10 MW	1 MW	10 MW
Electrode area	1 500 cm²	> 10 000 cm²	10 000-30 000 cm²	30 000 cm²
Cold start (to nominal load)	< 20 minutes	< 5 minutes	< 50 minutes	< 30 minutes
Capital costs (stack) minimum 1 MW	USD 400/kW	< USD 100/kW	USD 270/kW	< USD 100/kW
Capital Costs (system) minimum 10 MW	700-1400 USD/kW	< 200 USD/kW	USD 500-1 000/kW	< USD 200/kW

Figure 2. Electrolysers e future KPIs [10]

Brazil's electricity sources

Electric energy is one of the most important discoveries of modern science. Among the numerous benefits, it can be mentioned that it enables the economic development of nations, drives technological and scientific development, and improves the quality of life of communities around the world. However, electrical energy does not exist in the primary form, in nature, and therefore, it needs to be produced from other energy sources. Likewise, hydrogen also does not exist in the primary form in nature and also needs to be produced from other energy sources.

In Brazil, in 2021, 656,109 TWh of electricity were produced. The energy sources for electricity production were: hydro (362,818 TWh), natural gas (86,957 TWh), biomass (52,416 TWh), solar (16,752 TWh), wind (72,286 TWh), coal (17,585 TWh), nuclear (14,705TWh), oil derivatives (17,327 TWh) and other sources (15,263 TWh) [12].

Green energy in Brazil

The energy sources needed to produce so-called green hydrogen are biomass, wind and solar. In this work, the hydrogen production method used is based on wind and solar photovoltaic energy. Currently, the installed capacity of wind energy in Brazil is approximately 25.0 GW [13], 9970 wind turbines, distributed in 869 wind farms, present in 12 Brazilian states [14]; the installed capacity of photovoltaic energy is approximately 9.2 GW.

In addition, the potential for photovoltaic energy production is high, since the annual average value of the total daily solar irradiation data for the five Brazilian regions. The Northeast region has the greatest solar potential, with value mean daily total horizontal global irradiation of 5.49 kWh/m² and the normal direct component of 5.05 kWh/m². To the Southeast and Midwest regions show daily totals close to the global horizontal irradiation around 5.07 kWh/m 2. The mean global irradiation on the inclined plane at Southeast region presented a daily total of 5.26 kWh/m², while in the Midwest region it presented 5.20 kWh/m² [15].

The Brazilian potential for wind energy production is also high. The possible power is of the order of 145 GW, and the electricity generation capacity is 272,2 TWh at a height of 50 m. At many points there are occurrences of wind with a speed of more than 8 m/s at a height of 50 m spread across the country [16]. Só na região nordeste do País a capacidade estimada a 50m de altura é de 75 GW com potencial de geração anual de 144,3 TWh [16].

All of this shows that Brazil already produces electricity from renewable sources in a way that is mature enough to support an eventual green hydrogen program for the transport sector, whether powered by wind or solar energy or hybrid energy sources. Therefore, as said, this

work is dedicated to electrolysis powered by photovoltaic energy, wind energy and hybrid photovoltaic and wind.
The reason for the low penetration of hydrogen as a fuel is mainly due to the high cost for the final consumer [11]. As it is an electro-intensive process, the production cost of a plant connected to the grid is very high. So, the hope of the researchers is that electrolysis can be made viable, if produced with renewable electrical energy. Thus, in this work, three electrolysis plants will be considered for evaluation: 1) Photovoltaic solar electrolysis. 2) Wind electrolysis; 3) Photovoltaic solar electrolysis; 3) Hybrid Photovoltaic and Wind.

What is known about large-scale green hydrogen production

This research found several configurations of processes, technologies and configurations possible to produce green hydrogen in [17]. However, three configurations studied and simulated in [18] drew attention and are in line with the objectives of this work. They are: 1. Grid Connected; 2) Hybrid, and 3) Autonomous. These three configurations are shown in Figure 3.

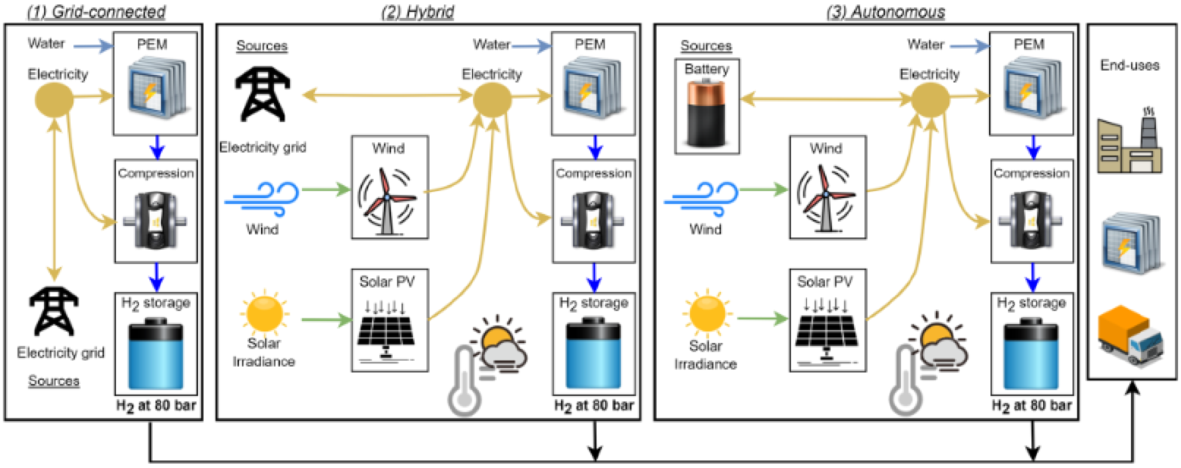

Figure 3. Hydrogen production configurations on grid, hybrid, and autonomous [18]

The grid-connected configuration consists of an electrolyser connected to the national electricity grid [18]. The hybrid configuration consists of a connection to the grid, as well as a direct connection to renewable sources of electricity, i.e. PV, onshore and offshore wind power. The main motivation for choosing this configuration is that hybrid systems can integrate renewable energy sources and can use the electrical grid as a backup supply and storage buffer. In addition, grid electricity can be used during periods of time with low grid electricity prices and to allow continuous operation of the electrolyser supplying the intermittency that exists in cases of PV and wind systems [18].
Standalone configuration is a power system layout, in which the electrolyser is fully operated by locally produced electricity from photovoltaic panels, and/or wind turbines completely disconnected from the grid. The motivation for choosing this configuration is not having access to the national grid power grid and so autonomous configurations are the only possible solutions in this situation. This can, however, lead to used renewable electricity generation and for oversized energy technologies [18].

What is known about costs of large-scale green hydrogen production

This research did not identify any large-scale green hydrogen plant in operation that could serve as a reference for comparing performance with the results obtained in this work. However, the topic is the subject of studies by many scientists around the world.

The work presented in [18] evaluated the production of hydrogen in Borkum in Germany, Crete in Greece, Eigeroy in Norway, Tenerife in Spain and Western Isles in Scotland by plants connected to the grid, by autonomous plants with conventional electrical energy, hybrid plants and hybrids only with green energy, as shown in the Figure 4.

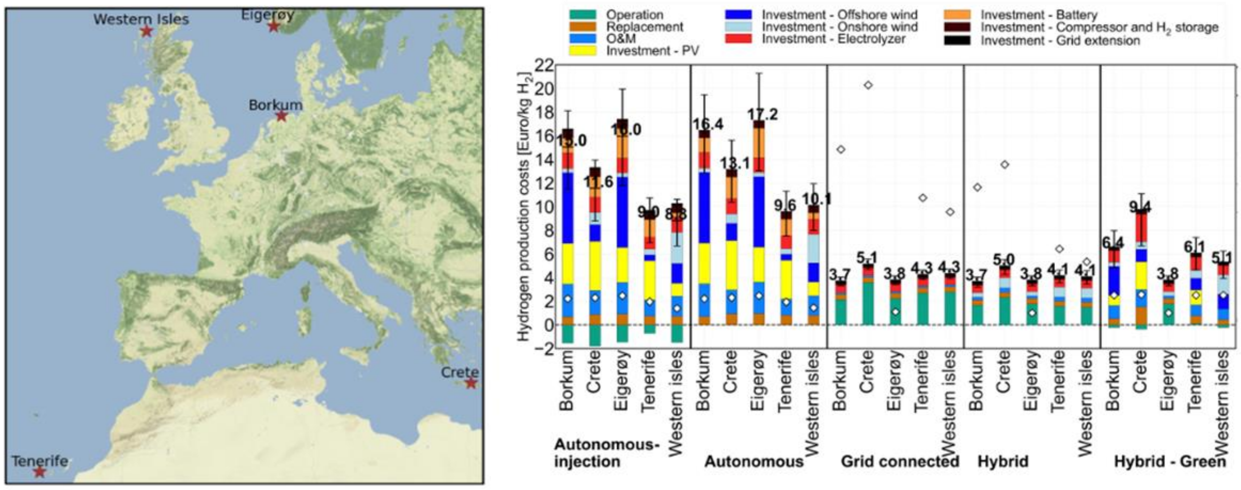

Figure 4. Hydrogen costs in Europe (Euro/kg) [18]

The Figure 4 shows that it is possible to produce hydrogen in Europe with costs ranging from 17.2 Euro/kg to 3.7 Euro/kg. It is also possible to affirm that the production cost of hybrid hydrogen with green energy ranges from 3.8 Euro/kg to 9.4 Euro/kg. It is easy to see that the cost of 3.8 Euro/kg in Eigeroy, 5.1 Euro/kg in Western Isles, 6.1 Euro/kg in Tenerife, 6.4 Euro/kg in Crete and 9.4 Euro/kg in Borkum.
On the other hand, studies published by the IEA [11], estimate that it is possible to produce green hydrogen in the world in range of 2.0 U$/kg to 8.0 U$/kg. Under the following conditions a) discount rate of 8%, b) the cost of electricity fixed at 40 U$/MWh and c) electrolyser capital costs in the range of 250 US/kW_e to 650 US/kW_e, it is possible to achieve green hydrogen costs in the range of 2.0 U$/kg to 4.0 U$/kg in the South America.
This research did not find any green hydrogen production plant in Brazil, however, the technical note that deals with the bases for the consolidation of strategy Brazilian hydrogen mentions that it is currently possible to produce green hydrogen with an approximate cost in the range of 1.50 U$/kg to 4.50 U$/kg; that the cost tends to decrease and that it will be in the range of 1.50 U$/kg to 2.75 U$/kg in 2030; and in the range of 0.70 to 1.70 U$/kg [19].

Hypotheses, objectives and questions of this research
In this context, this work was developed based on the hypothesis that it is possible to produce a lot of wind energy and, therefore, a lot of hydrogen in the Port of Pecém, in the Ceará Brazilian state in the Northeast of Brazil, with production costs lower than those obtained by the IEA, of 40 U$/MWh and hydrogen in the range of 2.0 U$/kg - 4.0 U$/kg, through electrolysis plants powered by photovoltaic, wind or hybrid energy. So, this research aims to evaluate the potential for green energy and hydrogen production in the region where the Port of Pecem is installed in the Northeast of Brazil, considering four scenarios and answering the following questions for each of them:

1) How much electricity is produced per year?
2) What the amount of hydrogen it is possible produced per year and per MW of power?
3) What is the cost of the electricity produced in U$/MWh?
4) What is the cost of the hydrogen produced in U$/kg?

5) After all, what is the best configuration for a large green hydrogen plant in the Port of Pecem region?

The four scenarios are:

A. The plant is powered with 100% of wind energy;
   1,000 kW in wind energy powering an electrolyser of 1,000 kW.
B. The plant is powered with 100% of photovoltaic energy.
   1,000 kW in PV energy powering an electrolyser of 1,000 kW;
C. The plant is powered by hybrid, wind and photovoltaic energy;
   1,000 kW in wind energy plus 1,000 kW in PV energy powering an electrolyser of 2,000 kW.

After answering the questions above, simulations of a large-scale hydrogen plant will be performed and the results of the configuration optimized by HOMER PRO will be presented, which can serve as a reference for a hybrid plant for centralized hydrogen production, for the environmental conditions of the Port of Pecem. This is the scenario D.

Key figures about the Port of Pecem

There are reasons for choosing the port of Pecem for this study. The first one is the prospect of becoming a hydrogen hub. It was announced investments in plants for the production of green hydrogen in Brazil add up to more than US$ 25 billion, the majority in port industrial complexes that combine fact strategic resources for the development of the hydrogen chain, such as logistics for export and proximity to renewable energy sources and industrial centers. The biggest part of the investments it is concentrated in the port of Pecém 54 km away from Fortaleza city (capital of Ceará state), which intend to form hubs in the hydrogen, concentrating research, production, storage and exportation activities [19].

The port of Pecém, the second largest in the Northeast of Brazil, signed 22 memorandums of understanding with the state government and companies such as Linde, Qair, Trans Hydrogen, Alliance, Eren do Brasil, Casa dos Ventos, Engie, Fortescue Future Industries and EDP Renova. Additionally, two pre-contracts were signed with Fortescue Future Industries, subsidiary of the Australian mining company Fortescue Metals Group, and with AES Brasil. The pre-contracts represent a step beyond memorandums and aim to advance in studies of pre-feasibility of green hydrogen projects. These projects are mainly aimed at export of hydrogen or its derivatives to Europe and add up to more than 8 GW in electrolysis capacity, with investments estimated at around US$ 20 billion [19]**.**

The Fortescue Future Industries will invest US$ 6,0 billion for production of green hydrogen with expected entry into commercial operation in 2025. The AES Brazil Will invest in a hydrogen plant for up to 2 GW of hydrogen and up to 800 thousand tons of ammonia green per year, focusing on exports to Europe. The Enegix Energy Pte Ltd will invest US$ 5.4 billion for annual production of 600 thousand tons of green hydrogen per year, using 3.4 GW of renewable energy [19].

The Transhydrogen Alliance will invest US$ 2.0 billion Production of 500 thousand tons of green hydrogen per year. the volume is equivalent to about 2.5 million tons of green ammonia, which will be exported from the Port of Pecém, in Ceará, to the port of Rotterdam, in the Netherlands. The Qair will invest US$ 6,95 billion for Production of green hydrogen with a capacity of 2.24 GW. the company will use electricity generated at the Dragão do Mar Maritime Wind Complex and of an offshore wind farm to be developed [19].

So, Brazil is face to face with the opportunity to enter a new global chain of value. The Brazilian energy matrix guarantees a privileged position, enabling the competitive production of hydrogen from a variety of sources, in particular of renewable energies. The vocation of the Northeast of the country for the production of wind and solar electricity at competitive costs, as well as its proximity to the European continent, qualify Brazil as a potential major producer

and exporter of hydrogen green. From the electrolysis of water, the largest component of the cost for the production of green hydrogen is wind or solar electricity [19].
The Port of Pecem is located 54 km from Fortaleza in the state of Ceará in Northeastern Brazil, at coordinates 3°33.1´S;38°49.9´W in a region where at a height of 4.5 m above sea level, the winds speeds is greater than 6.0 m /s is 90% of the time [20].

Energy Source Data for Pecem Port

Figure 5 shows Monthly Average Wind Speed Data in Pecém Port, where it is easy to see that at 50 m above the sea level the monthly average is 6.87 m/s, the minimum is 5.04 m/s in the month of April of each year and maximum is 8.5 m/s [21] apud [22].

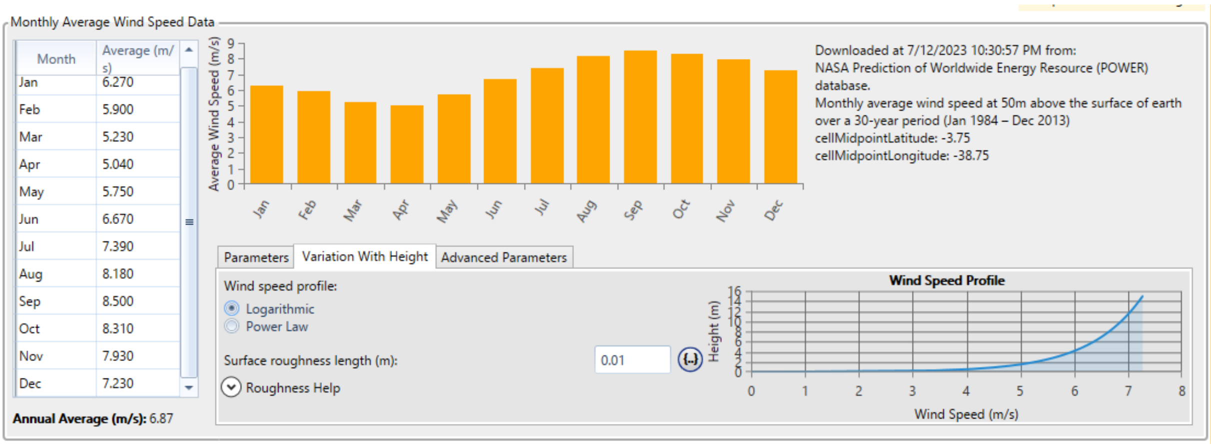

Figure 5. Monthly average wind speed data in the Pecém Port [21] apud [22]

The second reason is related to the high potential of photovoltaic energy, as shown in Figure 6. The average Global Horizontal Irradiance (GHI) in Pecem Port is 5.84 kWh/m²/day, the minimum is 4.77 kWh/m²/day, the maximum is 6.92 kWh/m²/day, which is converted into Global Irradiance by the HOMER PRO and results in at Global Solar Daily Profile [21] apud [22].

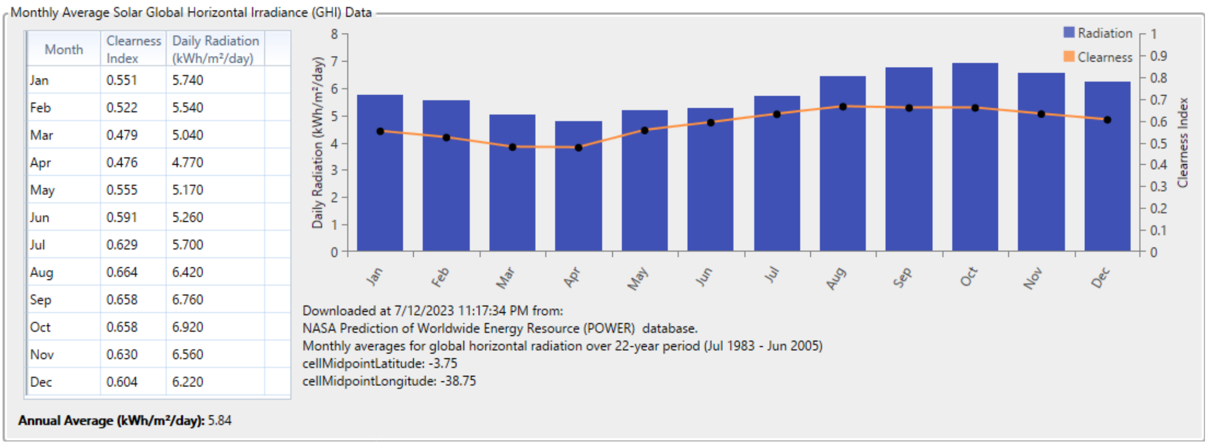

Figure 6. Monthly Average Solar Global Horizontal Irradiance in Pecem Port [21] apud [22]

Figure 7 shows that in Port of Pecem the sun rises before 06:00 AM in the morning and sets very close to 06:00 PM. This results in 4,349 hours of sunlight for energy production, as calculated by HOMER PRO for this job.

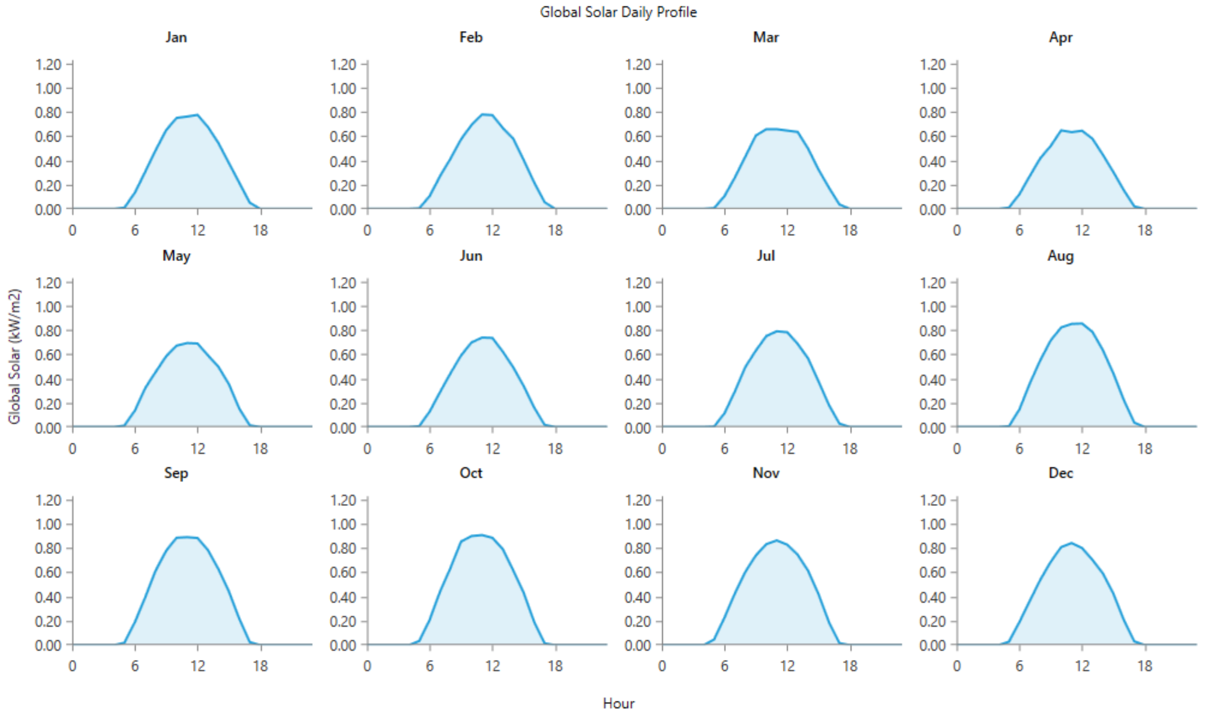

Figure 7 – Global Solar Daily Profile of Pecem Port [21] apud [22].

However, the annual average temperature is 26.69°C (Figure 8) and this contributes to increasing the temperature of photovoltaic cells and consequently reduction of the power generation capacity [21] apud [22].

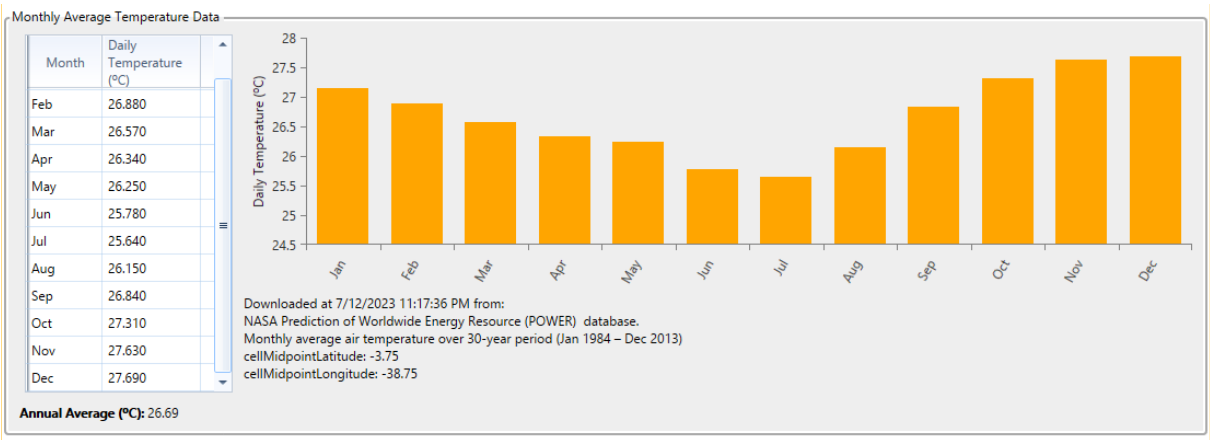

Figure 8. Monthly Average Temperature Data in Pecem Port [21] apud [22]

The data shown in Figures 5, 6, 7 and 8 are used as input data in the HOMER PRO to simulate and estimate the amount of electricity in Port of Pecem, in accordance with the methodology described below.

MATERIAL AND METHOD

The tool HOMER PRO

In this work the HOMER PRO 3.14.5 was used to perform the simulations. A Micro Power Optimization Model - HOMER PRO 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 [23].

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 [23].

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 [23].

Method

The approach followed in this research is demonstrated in the flowchart represented in the Figure 11, 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 plant object of this study, 2) Parametrization, 3) Simulation and optimization and 4) Sensitivity analysis of results, as described in [23].

The characterization of the plant consists of defining the components that compose it, creating the schematic diagram as shown in Figure 10, and defining the initial simulation condition in HOMER PRO.

Plant Characterization

The hydrogen plant object of this study is an autonomous plant, in which one or more electrolysers are directly powered by electrical energy produced in the plant itself, without any connection to the national grid. The reason for this choice is that this work is a continuation of previous work that used isolated systems as a premise. One of the assumptions is that the hydrogen produced can be classified as green hydrogen. The national network that feeds the port of Pecem contains energy produced from natural gas and coal thermoelectric plants. The schematic diagram of the plant considered in this study is shown in Figure 10.

Then, according to Figure 10, the components of the initial configuration of the plane will be an electrolyser fed by a PV energy generating unit available in a DC bar; an AC electric power generating unit produced by a wind turbine converted into DC through an AC/DC converter, which feeds the plant's DC bar; a bank of batteries connected to the DC bus of the plant; a hydrogen tank capable of storing all the hydrogen produced in predetermined periods; and three loads: the electrolyser, the AC power consumption bar of the plant and the hydrogen charge itself, to be produced by the electrolyser.

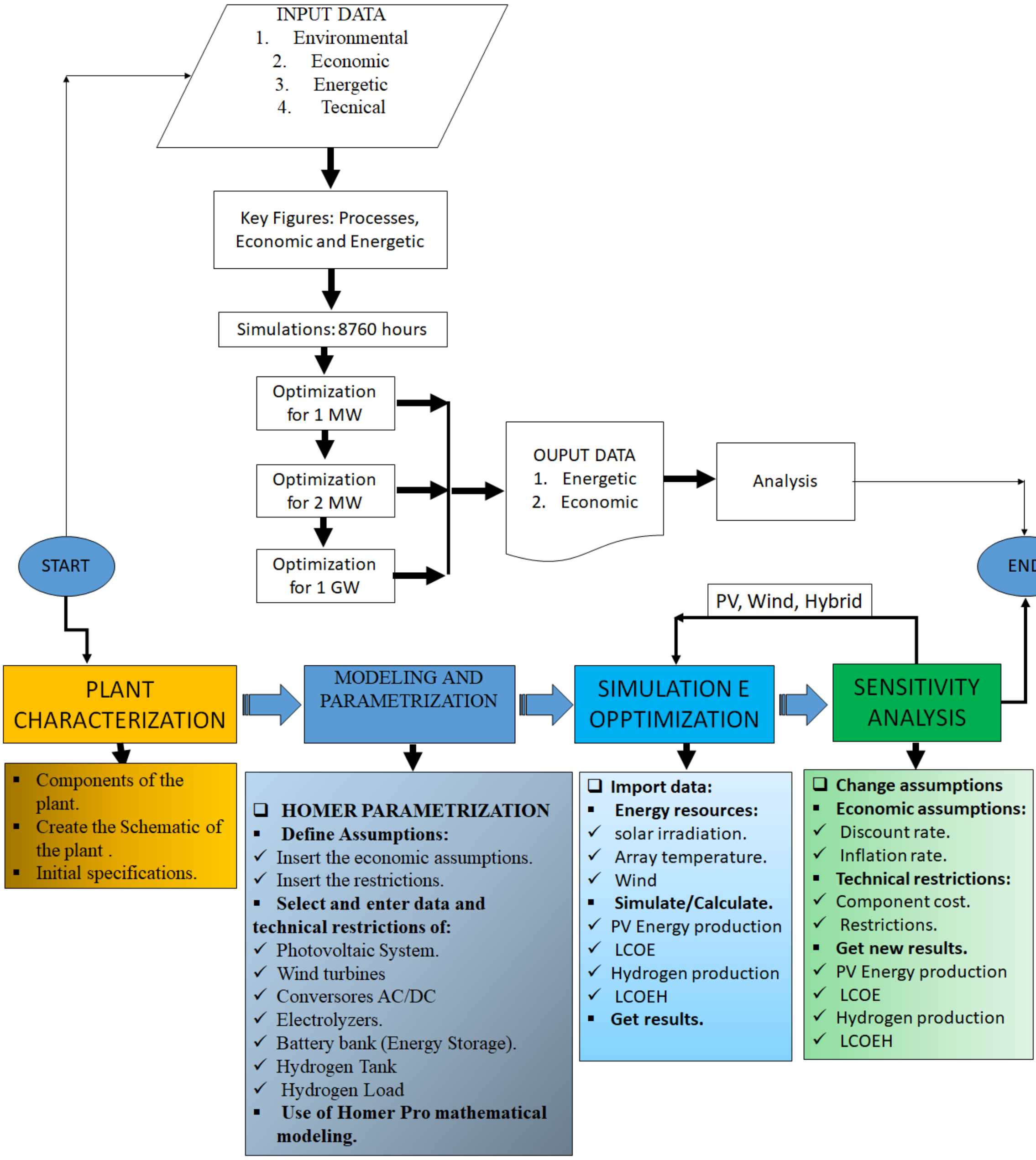

Figure 9. Flowchart of the dynamic simulation and optimization method, adapted from [24]

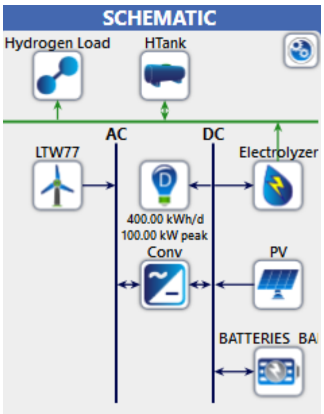

Figure 10. The plant object of this study

Modeling and Parametrization

HOMER simplifies the task of designing on-grid and off-grid power systems. HOMER's optimization algorithms and sensitivity analysis make it possible to assess the economic and technical feasibility of a large number of technology options and to take into account variations in technology costs and availability of energy resources. For this, it is necessary to parameterize HOMER PRO with the specific data of the system being studied, so that it can generate the necessary answers for the problem under study.

The parameterization data from this work were divided into three groups: design constraints economic assumptions and technical data of plant equipment.

In the group of design constraints, two parameters have been included: maximum annual capacity scarcity at 1.0%, which HOMER PRO will optimize, and minimum renewable fraction at 100%, since all energy sources are renewable.

In the group of economic assumptions are defined the discount rate, the inflation rate, project useful life and capital costs of each of the equipment of the initial and replacement plant, and their respective references, as shown in Table 1.

Table 1. Economic assumptions

ECONOMIC ASSUMPTIONS	Units	Value	REFERENCES
Discount Rate	%	8	[11]
Inflations	%	3	[25]
Project lifetime	year	25	[4]
EQUIP. CAPITAL COSTS			
Electrolyser	US/kW	450	[11-26]
PV System	US/kW	900	[1]
Capital costs of wind system	US/kW	1200	[27-28]
Energy Storage (Baterries)	US/Unit	200	[18]
Conversor	U$/kW	80	[29]
O&M	%	2	[18]

In the group of technical data of the equipment, the specific technical data of each of the equipment, as shown in Table 2, and their respective references, are presented.

Table 2. Technical data

COMPONENTS			
Generic ELECTROLYSER	Units	Values	REFERENCE
Efficiency	%	74	[26]
Capacity optimization	kW	1,000	Assumption
Electrical Bus	AC/DC	DC	Assumption
Lifetime	Years	10	[10]
Operation Mode		Optimized	Assumption
Generic PV SYSTEM			
Lifetime	Years	25	[5]
Derating factor	%	94	[21]
Electrical Bus	AC/DC	DC	Assumption
Operation Mode		Optimized	Assumption

WIND SYSTEM			
Wind turbine type		Leitwind 77	[21]
Rated Capacity	kW	1,000	[21]
Lifetime	Years	20	[21]
Hub heigth	m	80	[21]
Quantity	Units	1	Assumption
Operation Mode		Optimized	Assumption
Electrical Bus	AC/DC	DC	Assumption
Generic CONVERSOR			
Size	kW	1,000	Assumption
Efficiency	%	95	[21]
Lifetime	Years	15	[21]
Relative capacity	%	100	Assumption
CONTROLADOR			
Homer load following			[21]

Simulation and optimization

After entering the parameterization data, the data of the energy resources of PV energy, wind energy and temperatures are downloaded and the calculations are performed in HOMER PRO in an interactive and optimized way until the electrolyser power reaches 1.0 MW of nominal power. HOMER PRO, in turn, will issue a report containing several simulations and performance data for each one of them. The calculations that are of interest to this work are modeled in HOMER PRO according to the equations below.

Power output of the wind turbine

HOMER calculates the power output of the wind turbine in each time step using a three-step process. First, HOMER calculates the wind speed at the hub height of the wind turbine. Then it calculates how much power the wind turbine produces at that wind speed at standard air density. Finally, HOMER adjusts that power output value for the actual air density [21].

Calculating Hub Height Wind Speed

In each time step, HOMER calculates the wind speed at the hub height of the wind turbine using the inputs you specify in the Wind Resource page and the Wind Shear entry [21].

If it is chosen apply the logarithmic law, HOMER calculates the hub height wind speed using the Equation (1) [21]:

$$U_{hub} = U_{anem} \cdot \frac{\ln(Z_{hub}/Z_0)}{\ln(Z_{hub}/Z_0)} \quad (1)$$

Where:

U_{hub}= wind speed at the hub height of the wind turbine [m/s].

U_{anem} = wind speed at anemometer height [m/s].

Z_{hub} = hub height of the wind turbine [m].

Z_{anem} = anemometer height [m].

Z_0= surface roughness length [m].

Ln(…) = natural logarithm.

If it is chosen apply the power law, HOMER calculates the hub height wind speed using the equation (2) [21]:

$$U_{hub} = U_{anem} \cdot \left(\frac{Z_{hub}}{Z_{anem}}\right)^{a} \tag{2}$$

Where, a = power law exponent

Calculating turbine power output at standard air density

After HOMER to determine the hub height wind speed, it refers to the wind turbine's power curve to calculate the expected power output from the wind turbine at that wind speed under standard conditions of temperature and pressure. In the Figure 11, the red dotted line indicates the hub-height wind speed, and the blue dotted line indicates the wind turbine power output that the power curve predicts for that wind speed. If the wind speed at the turbine hub height is not within the range defined in the power curve, the turbine does not produce power [21].

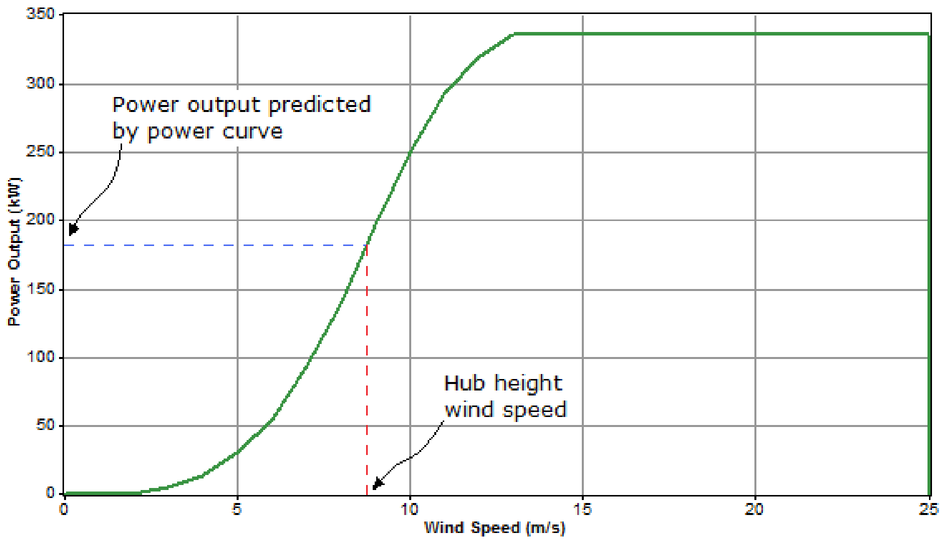

Figure 11. Wind turbine curve (output x wind speed) [21]

Applying Density Correction

Power curves typically specify wind turbine performance under conditions of standard temperature and pressure (STP). To adjust to actual conditions, HOMER multiplies the power value predicted by the power curve by the air density ratio, according to equation (3) [21]:

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) . P_{WTG,STP} \tag{3}$$

Where:

P_{WTG} = wind turbine power output [kW].

$P_{WTG,STP}$ = wind turbine power output at standard temperature and pressure [kW].

ρ = actual air density [kg/m^3].

ρ_0 = air density at standard temperature and pressure (1.225 kg/m^3).

Calculating the PV array out put

The Solar GHI Resource page allows to specify 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 [21]. HOMER uses the Equation (4) to calculate the output of the PV array [21]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STD}}\right)[1 + a_P(T_c - T_{c,STC})] \quad (4)$$

Where:
Y_P = the rated capacity of the PV array, meaning its power output under standard test conditions [kW].
$f_{PV} =$ factor dereting [%].
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 [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 [21]. Otherwise, it assumes that the temperature coefficient of power is zero, so the Equation (4) is simplified (5) [21]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STD}}\right) \quad (5)$$

Calculating 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 (6):

$$E_{PVout} = \int_0^{t1} P_{PV}\,dt + \int_{t1}^{t2} P_{PV}\,dt + \ldots + \int_{tn}^{8760} P_{PV}\,dt \quad (6)$$

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 (7) [21]:

$$\text{LCOE} = LCOE = (C_{ann,tot} - C_{boiler} H_{served})/E_{served} \quad (7)$$

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 (8) [21]:

$$C_{ann,tot} = CRC(i, R_{proj}).C_{NPC,tot} \tag{8}$$

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 [21].

Calculate LCOH - Levelized Cost of Hydrogen
HOMER PRO uses Equation (9) to calculate the LCOH - Levelized Cost of Hydrogen [21].

$$\text{LCOH} = [C_{ann} - V_{elet}(E_{prim,AC} + E_{prim,DC} + E_{def} + E_{grid,sales})]/M_{hydrogen} \tag{9}$$

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].

RESULTS
After characterizing the plant, parameterizing HOMER PRO, and downloading the energy resources of the region of Pecem Port, the command was given to perform the calculations, whose results needed to answer the questions of this research are shown below.
The HOMER PRO produces a comprehensive report with the results of the simulations that are highlight here, just the information necessary to answer the research questions and understand the results obtained for each scenario, which are presented in Table 3.

Energy produced
Table 3 shows the results obtained in three configurations and scenarios. The scenario A considers a plant with a 1,000 kW electrolyser powered only by a 1,000 kW wind turbine. In this configuration, the energy generated was 5,180,395 kWh, resulting from an average generation of 591 kW in 8,008 hours per year, whose daily generation curve for each month of the year is shown in Figure 12-A.

The scenario B considers a plant with an electrolyser of 1,000 kW powered only by a PV system of 1000 kW. In this configuration, the energy generated was 2,007,091 kWh, resulting from an average generation of 229 kW in 4,349 hours per year, whose daily generation curve for each month of the year is shown in Figure 12-B.

In scenario C, it is considered a plant with an electrolyser of 2,000 kW powered by a wind turbine of 1,000 kW and PV System of 1,000 kW. In this configuration, the energy generated was 7,262,752 kWh, of which 72.1% were produced by the wind turbine and only 27.9% was produced by the PV System, resulting from an average generation of 821 kW in 8,008 hours per year, whose daily generation curve for each month of the year is shown in Figure 12-C.

Thus, the first research question was answered.

Table 3. Summary of the results

		Scenarios		
	Units	**A**	**B**	**C**
Total rated capacity of wind turbine	kW	1,000	0	1,000
Total rated capacity of PV system	kW	0	1,000	1,000
Total rated capacity of the electrolyser	kW	1,000	1,000	2,000
Amount of electricity produced	kWh/year	5,180,395	2,007,091	7,262,752
Cost of electricity produced (LCOE)	U$/kWh	23.40	40.40	27.85
Amount of hydrogen produced	kg/year	88,814	34,343	125,193
Cost of hydroge produced (LCOH)	U$/kg	2.77	4.44	3.39
Time of wind turbine in operation	hours/year	8,008	0	8,008
Time of PV system in operation	hours/year	0	4,349	4,349
Average output of the wind turbine	kW	591	0	591
Average output of the PV system	kW	0	229	229
Time of electrolyser in operation	hours/year	7,011	3,462	7,011
Maximum demand of electrolyser	kW	933	1,000	2,000
Energy consumption of electrolyser	kWh/year	4,734,079	1,830,613	6,673,194
Electrolyser conversion rate	kWh/kg	53.3	53.3	53.3
Excess electricity	%	1	1.52	1.6
Capacity Shortage	%	0.53	0	0.32

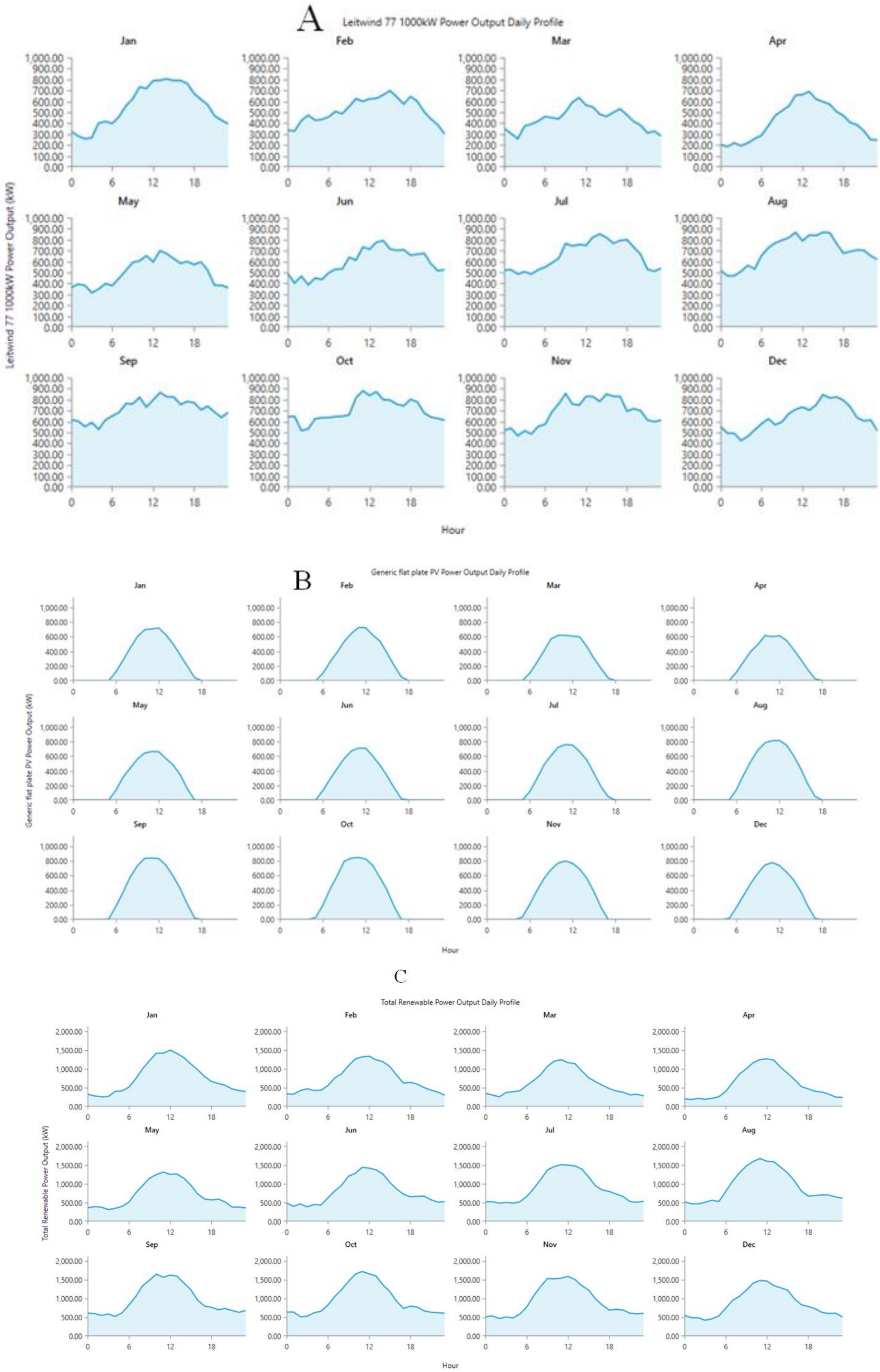

Figure 12. Energy produced in scenario A, scenario B and scenario C

Hydrogen produced

Table 3 showed that a 1,000 kW electrolyser is capable of producing up to 88,814 kg/year of hydrogen when powered by a 1,000 kW wind turbine; however, the same electrolyser fed with a PV system, is only capable of producing 33,343 kg/year of hydrogen. A hybrid wind and photovoltaic system is capable of producing 62,587 kg/year with a 1,000 kW electrolyser.
So, it is possible to conclude that better results in terms of the amount of hydrogen production per 1,000 kW of power are obtained when using wind energy, than when powered by PV systems or by a hybrid system of the same power. Thus, the second research question was answered.

Production Costs

The Table 3 also shows the costs of producing electricity and hydrogen for each of the configurations. It is easy to see that it is possible to produce energy from wind energy with LCOE at 23.40 U$/MWh, photovoltaic energy with LCOE at 40.40 U$/MWh and hybrid energy at the LCOE of 27.85 U$/MWH. This shows that producing electricity from wind energy in the area of Porto de Pecem is more economically viable than photovoltaic and hybrid energy. So, in cases of hybrid power plants, the lower the share of photovoltaic energy, the better the final cost of the electricity produced.
Finally, Table 3 also shows that it is possible to produce hydrogen from wind energy with LCOH at 2.77 U$/kg, from photovoltaic energy with LCOH at 4.44 U$/kg and from hybrid energy at the LCOH of 3.39 U $/kg. So, in the same way as with electrical energy, in cases of hybrid power plants, the lower the share of photovoltaic energy, the better the final cost of the hydrogen produced.

Results for large scale production – scenario D

The HOMER PRO reported on 77 large-scale hydrogen plant simulations of which 36 were considered feasible. Table 4 shows the results of the most feasible configuration: electrolyser with 1.0 GW, wind energy installations of 1.0 GW and photovoltaic energy installations of 352.51 MW, maintaining all other conditions of the previous simulation.

Table 4. Large Scale hydrogen plant

	Units	Scenario **D**
Total rated capacity of wind turbine	GW	1.0
Total rated capacity of PV system	MW	352.51
Total rated capacity of the electrolyser	GW	1.0
Amount of electricity produced	GWh/year	5,886
Cost of electricity produced (LCOE)	U$/kWh	25.40
Amount of hydrogen produced	t/year	97,342
Cost of hydroge produced (LCOH)	U$/kg	2.72
Time of wind turbine in operation	hours/year	8,008
Time of PV system in operation	hours/year	3,349
Average output of the wind turbine	MW	591,4
Average output of the PV system	MW	80,56
Time of electrolyser in operation	hours/year	7,336
Maximum demand of electrolyser	GW	1.0
Energy consumption of electrolyser	GWh/year	5,188
Electrolyser conversion rate	kWh/kg	53.3

Excess electricity	%	4,77
Capacity Shortage	%	0.0

It is easy to see in Table 4 that an electrolysis plant with an installed capacity of 1.0 GW in Pecem is capable of producing 97,420 tons of hydrogen per year, when fed by 1 GW of wind energy and 352.51 GW of photovoltaic energy. In addition, it is easy to see that the LCOH of hydrogen is around 2.72 U$/kg, and therefore, it is in the middle of the estimated production cost range estimated by the IEA. So, it is possible to say that the initial hypothesis of this work has been verified. The performance of the electrolyser can be seen in Figure 13.

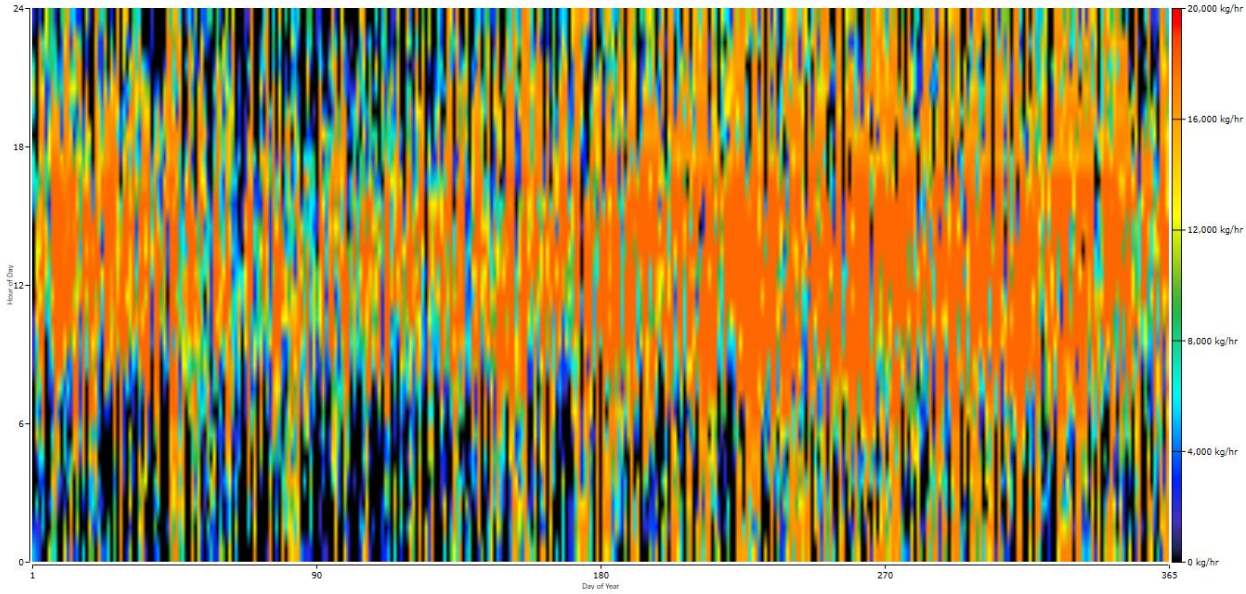

Figure 13. Electrolyser performance

From the data that generated the Figure 13 by the HOMER PRO, it is possible to extract that: the electrolyser operated at a rate greater than 15,000 kg/h more than 44% of the time; the maximum annual average flow is 18,733 kg/h and occurs in the month of October of each year; the highest monthly average was 13,198 kg/h and occurs in September of each year; the lowest monthly average was 7.872 kg/h and occurs in April of each year. In addition, the average flow is 11,112 kg/h when the electrolyser operates 7,336 h/year and has a conversion rate of 53.3 kWh/kg of produced hydrogen.

CONCLUSIONS

This work fulfilled the initially foreseen scope, simulating and evaluating an electrolysis plant powered by hybrid energy, equipped with a wind turbine integrated with a photovoltaic system, for the environmental conditions near the Port of Pecem, in the state of Ceará, in Northeastern Brazil, for the four proposed configurations. And, considering the restrictions and assumptions established throughout the work, it is possible to conclude that:

1) It is possible to produce a considerable quantity of electricity and hydrogen in the Port of Pecem;

2) A large-scale hydrogen plant, equipped with 1.0 GW of electrolyser and powered by hybrid energy of 1.0 GW of wind energy and 352 MW of photovoltaic energy is capable of producing an amount of 5,886 GWh/year and 97,342 tons of hydrogen per year, with costs LCOE of 25.40 U$/MW and LCOH of 2.72 U$/kg, respectively;

3) That the wind conditions in Pecem allow operating and producing electricity 8008 hours a year, at a LCOE cost of 23.4 U$/MWh, making this type of energy more viable than photovoltaic energy, whose LCOE is 40.40 U$/MW;
4) The hybrid energy option must consider the minimum necessary share of photovoltaic energy and the maximum share of wind energy, due to the final cost of energy and hydrogen;
5) The two initial hypotheses of this work were verified: a) It is possible to produce energy in Pecem at a cost lower than 40.0 U$/MWh, and b) It is possible to produce hydrogen with a cost in the range of 2.0 to 4.0 U$/ kg;
6) These results are in line with studies by the IEA - Energy International Agency.
Finally, for future steps, it is recommend that the hypothesis of this work be tested, close to the Port of Suape, in the state of Pernambuco, also in the Northeast of Brazil, where there is an abundance of renewable energies.

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NOMENCLATURE

AEC - Alcaline Electrolyser
AEM - Anion Exchange Membrane Electrolyser
BEN - National Energy Balance
CCS - CO_2 Capture and Storage
DC - Direct Current.
GHI - Horizontal Global Irradiation
HOMER PRO - Hybrid Optimization of Multiple Electric Renewables
IEA - International Energy Agency
KPI - Key Performance Indicators
LCOE - Leveled Cost of Energy
LCOH - Leveled Cost of Hydrogen
NASA - National Aeronautics and Space Administration
NEREL - National Renewable Energy Laboratory
NG - Natural Gas
O&M - Operation and Maintenance
PEM - Proton Exchange Membrane Eectrolyser
PV - Photovoltaic
SMR - Steam Methane Reform
SOEC - Solid Oxid Electrolyser

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