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(RESEARCH ARTICLE)

Potential of solar hydrogen production by water electrolysis in the NEOM green city of Saudi Arabia

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Abstract

Green hydrogen is one of the new and promising renewable energy sources, and there is a growing recognition that hydrogen will be the fuel of the future. While numerous methods may be used to manufacture hydrogen, only a few of them are ecologically benign. It is argued that solar hydrogen generated from water using solar energy is a leading candidate for renewable energy. Also, one of the most critical challenges facing green hydrogen is its production as an environmentally safe energy source. Moreover, there are several ways to produce it, including through solar panels alone. In this research, a review will be made of the most important research that has studied the production of green hydrogen using solar energy alone or using different sources of renewable energy so that the system becomes a hybrid. The HOMER Pro program makes a technical study of many scenarios and selects the best ones. In this research, the focus was on hydrogen production in the city of NEOM in the Kingdom of Saudi Arabia, because it is one of the most important pillars of Saudi Arabia's vision of 2030, and it will be the largest exporter of green hydrogen in the world. The HOMER Pro program was used to simulate hydrogen production through solar panels distributed over 100 square meters, and the amount of hydrogen produced was measured and compared with other cities in the Kingdom of Saudi Arabia. Through simulation, it was concluded that the city of NEOM has high potential in the production of green hydrogen, due to several reasons, the most important of which is the amount of solar radiation falling on it, in addition to being close to a source of water for the process of hydrogen separation from water.

Keywords: Electrolyzers; Green Hydrogen; Neom green city; Photovoltaics; Solar hydrogen production; Saudi Arabia

1. Introduction

1.1. Hydrogen Technology in KSA

The major source of energy for 150 years has been fossil fuels, e.g., petroleum [1]. Due to air pollution and that the current ways of obtaining energy such as petroleum are non-renewables, human beings need to find new ways of producing energy. Hydrogen is an element found on earth which can be chemically converted to green energy. The advantage of extremely reached solar energy is that it is one of the most promising energy sources among those available for its tremendous amounts of energy-saving and carbon emissions reduction [2]. Electrolysis using solar energy as an excellent commercial source of hydrogen from water has been pursued for more than three decades [3]. Green hydrogen is important since it is clean energy and one of the abundant chemical elements in nature. the International Energy Agency claims, internationally demand for hydrogen as a fuel has more than quadrupled since 1975, earning 70 million tons per year in 2018. Furthermore, it is a clean energy source, emitting just water vapor and

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leaving no residue in the air. Unlike coal and oil, it offers a variety of industrial and medical applications. The most essential component is hydrogen, which is considered the future of renewable energy.

Although hydrogen is essential for its use as a fuel, there are problems in return, which is that 95% of the hydrogen produced in the world has emissions that affect the ozone layer, known as the Greenhouse effect [4]. Therefore, it was necessary to find alternative ways to produce hydrogen without any emissions that may negatively affect the environment, and the solution was to produce hydrogen with renewable energy. One of the most important renewable energy systems is solar energy, especially in Saudi Arabia because it is located in the middle of the sunbelt. One of the most critical problems and challenges facing the energy extracted from hydrogen is how to store it, mainly because hydrogen under standard conditions is a gas, highly flammable, colorless and odorless.

This research will address the challenges facing hydrogen in the Kingdom of Saudi Arabia, starting from its production with solar energy and the necessary calculations for this, considering the environment of the Kingdom of Saudi Arabia and the methods of storing it.

The main goal of this project is to generate hydrogen gas using solar energy, because this method of hydrogen production relies on inexhaustible sources, such as water and solar radiation, which can be converted into electrical energy by silicon solar cells, and hope to obtain clean and sustainable energy with a 100% reduction in emissions. In this table (Table 1), the physical and chemical characteristics of hydrogen when used as a fuel are shown:

Table 1 Characteristics of hydrogen as a fuel or energy carrier [5]

Theoretical energy equivalent for the reaction: $2H_2 + O_2 \rightarrow 2H_2O$	MJ / kg H_2	120.6
	kWh / kg H_2	33.5
	kWh / m^3 H (1)	3.00
Electrochemical decomposition potential of pure water to $H_2 + O_2$, V		1.24
Heating value, MJ / kg H_2	Lower	114.5 – 119.9
	Higher	135.4 – 141.8
Hydrogen content in the stoichiometric combustible mixture, vol.%	Hydrogen – air	29.53
	Hydrogen – oxygen	66.67
Temperature of self-ignition of the combustible mixture, °C	Hydrogen – air	510–580
	Hydrogen – oxygen	580–590
Flame temperature, °C	H_2 – air, stoichiometric Mixture	2235
	H_2 (73.0 vol.%) – O_2	2525
Concentration limits of hydrogen burning in the mixture, vol. %:	Hydrogen – air	4.1–72.5
	Hydrogen – oxygen	3.5–94.0
Concentration limits of detonation in the mixture, vol. %:	Hydrogen – air	13–59
	Hydrogen – oxygen	15.5–93
Maximum flame propagation speed, m/s	Hydrogen – air	2.6–3.4
	Hydrogen – oxygen	9–13.5
Extinguishing distance for hydrogen – air stoichiometric mixture, mm(2)		0.6–0.8
Minimum energy for the ignition of stoichiometric mixture $H_2 + O_2$, mJ		0.02

Notes: (1) – at normal conditions: P=1.01308 bar, T=0 °C; (2) – P=1.010085 bar, T=25 °C

1.2. Renewable Energy in Saudi Arabia

Saudi Arabia is located in the sun belt, which gives the country strong sun radiation [6]. Solar hydrogen is one method of producing hydrogen using the sun. This method is green and possible to be generated in Saudi Arabia, the country invests in renewable energy sources by achieving some novel green cities, such as NEOM. NEOM is a 475 billion USD megacity in Saudi Arabia that will be constructed on its border with Egypt. It will be centered at 28°13.2′ latitude north, 34°53.3′ longitude east, and will have an approximate area of 26,000 square meters serving a large population.

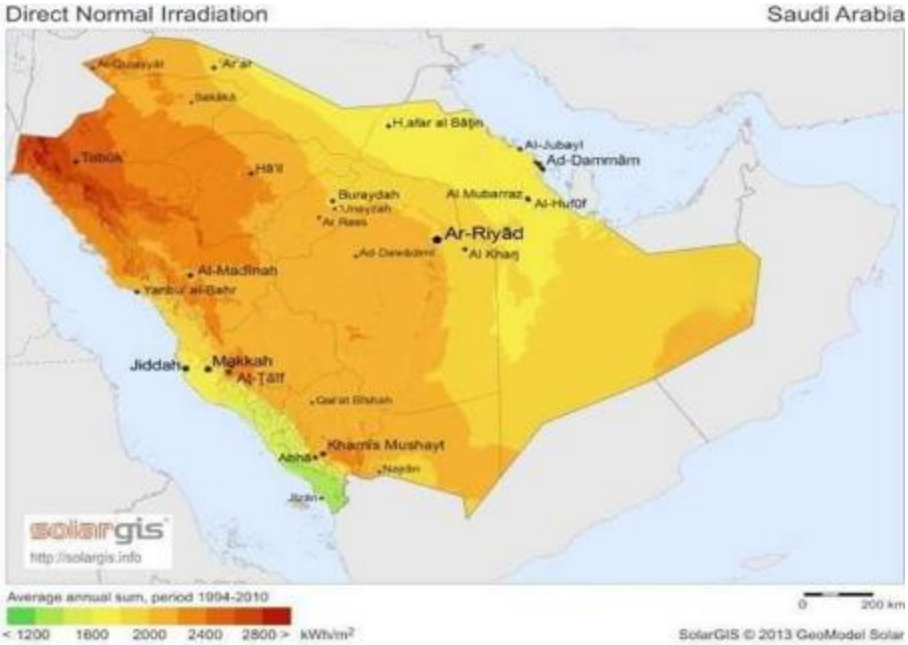

Figure 1 The Direct Normal Irradiation of Saudi Arabia (1994-2010) (Saudi Solar)

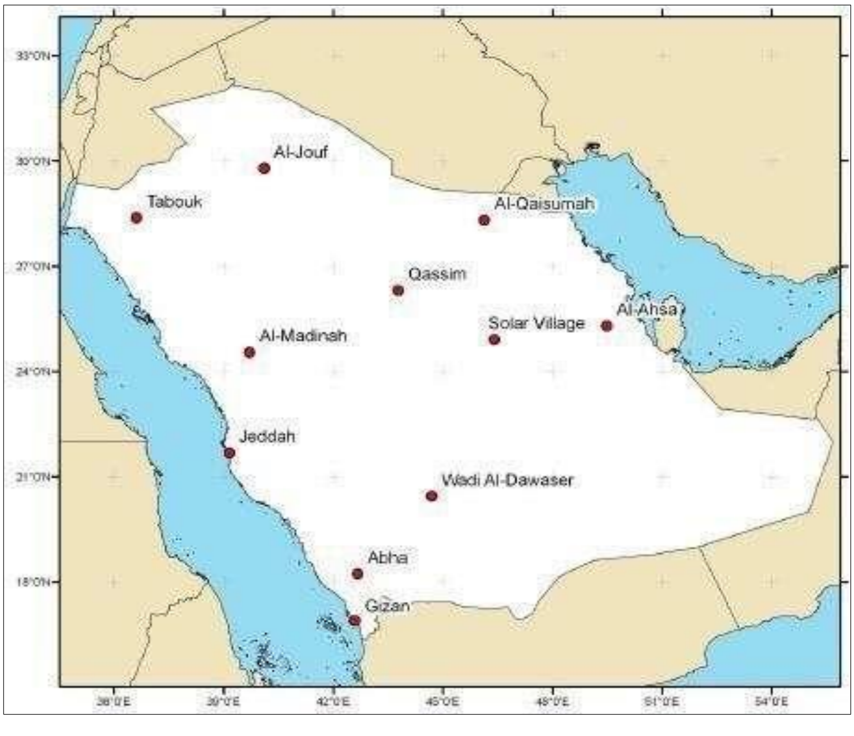

Figure 2 The location of Solar Village in Saudi Arabia

Its energy is considered to be used from renewable sources such as solar power, biomass, or wind energy. In fact, one of the major users of the electrical energy is the hospitals, for which these solar plants need to have a sustainable supply of electricity, while a portion of this energy needs to be stored. The Sustainable Development Unit (SDU), which was founded in 2008 by the United Kingdom's National Health Service (NHS), defined sustainable healthcare as "delivering high-quality care and improved public health without exhausting natural resources or causing severe ecological 3 damage" [7]. Besides, there are plans to build a green hydrogen plant in Saudi Arabia that will operate with 4 gigawatts of wind and solar energy, which is the largest project of its kind in the world announced so far. This carbon-free fuel is made from water by using renewable electricity to separate hydrogen molecules from oxygen molecules. The project will be in NEOM, a new mega city planned near the borders of the Kingdom of Saudi Arabia with Egypt and Jordan. The completed facility will produce 650 tons of green hydrogen per day, enough to power about 20,000 hydrogen-fueled buses, and the fuel will be shipped in the form of ammonia to final markets globally and then converted back into hydrogen. Ammonia production is expected to begin in 2025 [8]. This study aims to investigate the potential of power generation and hydrogen production via solar resources at different locations in the Kingdom of Saudi Arabia. These locations represent the variety of climatic conditions in the Kingdom with other solar radiation and wind speed potentials. At each location, there will be different renewable off-grid power sources. Global warming and the associated environmental pollution have caused huge effect on life on the Earth during recent decades. Nowadays, there has been a significant support to utilize new clean energy resources. Renewable energy resources have gained huge attention to earn environmentally friendly power installation [9-10]. Figure 3 shows the design of the solar hydrogen production system.

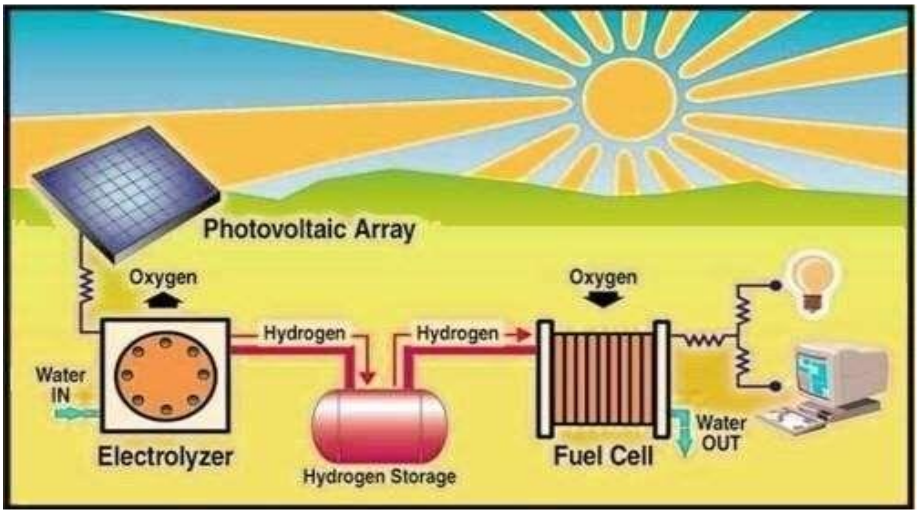

Figure 3 Hydrogen production from solar energy [11]

Even though the Kingdom of Saudi Arabia is main economy based on fossil fuels, it has the ability to established renewable energy sources. Saudi Arabia's capabilities in the production, transmission, and development of renewable energy sources are advancing at a rapid pace. Saudi Arabia is experiencing economic growth, with a 5.31 percent average age change in real GDP [12]. The Kingdom of Saudi Arabia has made significant efforts in the area of renewable energy in all of its forms, with solar energy, wind energy, and hydrogen energy being the three most important categories on which the Kingdom focuses. Saudi Arabia plans to create roughly 42 GW of solar energy in 2030, and 9 gigawatts of wind energy in 2040, The Kingdom of Saudi Arabia has taken big steps in the field of hydrogen energy with NEOM, where those who can utilize it to generate energy can also use it in chemical processes [13].

1.3. Solar Energy

Solar energy is the most promising resource of energy due to the availability of the sun. However, not all areas in the world have strong sun radiations which leads to less energy gained by the sun [14]. The increase of energy demand has risen in the last four decades and the reduction in fossil fuels has been growing due to the carbon dioxide emissions. Solar energy is clean source and free to all the world [15]. The usage of solar energy goes back to the 7th century BC when magnifying glasses were used to concentrate the sun's rays to make fire and to burn ants [16]. Nowadays, solar is used to generate energy from the sun to power homes, schools, buildings, factories … etc. In the kingdom of Saudi Arabia solar energy is used to produce electricity. The focus of KSA is to have renewable energy sources to power the country instead of using fossil fuels.

1.4. Green Hydrogen Technology

Hydrogen is a promising commercial energy source because of its abundance and the ability to produce it in a cleaner form that can replace fossil fuels, which is more appealing than water through electrolysis, making it an option that addresses the challenges of decarbonizing certain areas (transportation, industries, storage) and depletion of tropospheric ozone and global climate change. Recently, a number of potential remedies to the present environmental issues caused by dangerous pollutant emissions have emerged [17-18]. Hydrogen energy systems appear to be one of the most successful options and have the potential to play a big part in improving the environment and ensuring sustainability [19-20]. At the moment, hydrogen is mostly utilized as a chemical material rather than a fuel, with a market value of around fifty billion US dollars for 40 Mt yearly production. The majority of its present applications are as a processing agent in oil refineries (for example, desulphurization and upgrading conventional petroleum) and in chemical manufacturing processes (e.g., methanol, ammonia and pharmaceuticals). The prospects of future population growth as a result of increasing demand for food and other commodities has led to the reasonable conclusion that demand for hydrogen will also rise, at least to meet the demands of traditional transportation fuels, fertilizers, and chemicals [21]. Green hydrogen generation methods are not now available at a suitable cost and efficiency. One green hydrogen production technology that may be considered a reference and which can be accomplished with off-the-shelf components is PV electrolysis: it links a photovoltaic (PV) power generating system with a water electrolyzer [22]. Investigations can be conducted into the efficiency, efficacy, and cost-effectiveness of this approach for large and small-scale hydrogen generating applications. Hydrogen may be found in a wide variety of natural compounds. Water is naturally found as brine (sea water), river or water, rain or well water, and is the most numerous of all. Hydrogen may also be extracted from fossil hydrocarbons, biomass, hydrogen sulfide, and a variety of other materials. When hydrogen is extracted from fossil hydrocarbons, all carbon dioxide must be treated (separated, sequestered, etc.) so that no GHG or other pollutants are released into the environment, and the hydrogen extraction process may be referred to as "green." The types of energy required to extract hydrogen from the above-mentioned natural resources fall into four categories: thermal, electrical, photonic, and biological. These types of energy are available from renewable energy sources.

1.5. Overview of Hydrogen

Hydrogen is a renewable element found on earth. Hydrogen has been used as fuel for more than 100 years but has never been considered as a future fuel. Nowadays, humans have realized that petroleum, which is the current fuel for the world, is not renewable and produces tremendous amounts of carbon emissions. Carbon emissions will lead the world into global warming and air pollution [5]. In order for the United Nations to protect the world, the Paris conference has been taken place to fight global warming and offer a friendly source for people, such as hydrogen [23]. Hydrogen has a high level of efficacy which is different from diesel or petroleum [24]. In countries like Saudi Arabia where the economy is based on oil production, the country considers hydrogen as a future source with zero emissions of carbon dioxide. Saudi Arabia has huge projects for hydrogen production, such as NEOM and Aramco hydrogen gas station. By taking hydrogen as a fuel in Saudi Arabia, it will lead the country into the green environment and a healthier life. Saudi Arabia set 2030 as the vision for the country towards a new world of renewable energy. By 2030 Saudi Arabia will be changed to a green country by applying many hydrogen projects. Even though the price for hydrogen tanks is expensive, in the near future the prices will drop down due to people's needs and affordable means of production. Also, the availability of hydrogen fuel locally will lead the market to reasonable prices.

2. Literature Reviews

2.1. Methods of green hydrogen production

2.1.1. Solar Energy

Solar energy is one of the most necessary sources of renewable energy, and it is the most abundant source of various renewable energy sources. [25] The sun emits approximately 3.8×10^{23} and about 1.8×10^{14} comes to the Earth. Solar energy comes to the earth in several forms, including heat and light [26]. Hydrogen is produced through solar energy by utilizing sunlight or its heat, and energy is produced in different forms [27].

2.1.2. Electrical Energy

This method is used when water passes through electrochemical processes to separate water into two components, water, and air. At room temperature, the water separation process is fragile due to the electrical conductivity of water, which reaches 10^{-7} moles/liter. Therefore, acids or bases are added to increase the electrical conductivity [28].

2.1.3. Thermal Energy

This method uses the solar collector to collect the heat from the sun, the molten salt is heated, then enters a heat exchanger, the water is heated, and then sent to PEM electrolysis, and then the water is analyzed into its oxygen and hydrogen molecules, then the hydrogen is compressed and stored in tanks [29].

2.1.4. Biochemical Energy

This method is used by chemical reactions in biomass and sunlight, which is called photo biolysis. In general, the efficiency of using bio-chemical processes to produce hydrogen is generally low. Green algae and cyanobacteria are among the most important microorganisms that generate hydrogen when exposed to light radiation [30].

2.1.5. Wind Energy

Hydrogen cannot be found alone on earth. It is dependent on another element. Wind energy can provide green hydrogen from offshore wind [31]. Since many methods of hydrogen are available, the more expend of hydrogen humans get. In future green hydrogen will become an important source for energy since it has zero carbon emissions.

2.1.6. Geothermal Energy

The depths of the earth are dug up to 4-6 km, and hot water is extracted, which is at a temperature ranging between 120-370 degrees Celsius, and this heat is used to generate electricity through steam engines or turbines in the production of hydrogen [32].

2.1.7. Biomass Energy

Hydrogen production from biomass allows an increase in production quantity and reduces greenhouse gas emissions. Furthermore, because of its natural cycle, this biomass might be carbon neutral. During photosynthesis, CO2 is utilized for plant development through biomass-derived hydrogen. Several technologies now produce H2 from biomass, such as thermochemical processes, biological transformations, and electrochemical generation [33].

2.1.8. Ocean Thermal Energy

OTEC (Ocean thermal energy conversion) is a constantly accessible renewable energy resource that might contribute to the baseload power supply combined with ocean energy sources. [34] The resource potential for OTEC is thought to be bigger than that of other ocean energy sources. [35] Up to 88,000 TWh/yr. of power would be gained from OTEC without having side effect om the ocean's thermal structure [36].

2.2. Literature Review of Solar Hydrogen Production by HOMER Pro

A literature review was conducted to find out what researchers have reached in different regions of the world in hydrogen production with solar energy. It is summarized in the following: Nader Barsoum, in this article, the configuration of the hybrid system is provided. This system is off-grid and deals with PV, hydro, diesel generator, converter, batteries, fuel cell, electrolyzer, and hydrogen tank modeled in HOMER software. HOMER is used to find the most cost-effective configuration among different simulated systems to achieve the objective of the least possible Levelized Cost of Energy (LCOE) for a given system under a proposed load of 75 kW.[37] Tania Khadem represent the technical and economic benefits of hydrogen storage base irrigation systems in agriculture. In this article, water is applied as a sustainable and clean source for hydrogen generation. In this journal, HOMER is used for the based Irrigation System. As well as a hydrogen fuel cell system, HOMER was also used to gain the monthly average required loads for the hydrogen fuel cell. Finally, HOMER was used to earn output results of solar radiation.[38]. the aspect of operation is to apply the PV system or wind turbine to meet the demand whenever possible to short the losses in the battery and fuel cell. while excess wind or PV energy is available, power is used first to the batteries, then to an electrolyzer, which consumes water to gain hydrogen for storage. The batteries or the fuel cell is then applied to meet the load when the wind or solar energy is insufficient. HOMER select whether to apply energy from the battery, fuel cell, or both based on the replacement cost and O&M of the devices. Because this analysis neglects O&M and because the fuel cell is not replaced during its lifetime, HOMER apply the full extent of the fuel cell capacity for this system before applying the batteries.[39]

OH, Mohammed, this article collaborates with the optimal design of a stand-alone hybrid photovoltaic and fuel cell power system without battery storage to use the electric load demand of the town of Brest, Western Brittany in France. In this research, HOMER was used for a design of the proposed PV/FC hybrid system, per hour average load differences in a year for every month, daily average load for a whole year, and monthly average daily solar radiation.[40]

A techno-economic analysis was studied in this article for a 100% renewable energy-according to standalone microgrid system comprising solar PV, battery energy storage, and Power to Hydrogen (P2H) system (having of an Electrolyzer, Fuel Cell, and Hydrogen Storage Tank). The microgrid schematic optimization method HOMER Pro was apply to design, model, and simulate the energy technologies and analyze and compare the energy balance, economics, and environmental emissions amongst the proposed scenarios.[41]

A Homer Pro program was selected to modify optimal component sizes, achieve the stander COE in each scenario, and cover the daily load and three days of autonomy. Solar irradiance, temperature, and weather information were gathered from NASA internationally data into the Homer Pro software as a settlement detonation. The simulation output proved that the hydrogen-battery hybrid energy storage system is the most cost-effective scenario. However, all gained scenarios are technically reasonable and economically comparable in the long run, that every has different merits and obstacle.[42]

This study describes a method for designing aspects of a hybrid power system for educational institutions. The goal of this project is to model, calculate, and develop a hybrid power system. A biomass gasification generator set, solar cells, and fuel are combined with a battery storage system to satisfy the power center's partial load requirements in Manit Bhopal, India. For this project, the calculating tool HOMER Pro 3.2.3 was utilized. HOMER Pro is a design simulation model that examines a hybrid power system's scalability, cost, and control approach. The AC base load of 101 kWh/day of power consumption is fed by these hybrid power systems, which have a maximum load requirement of 5 kW. The best component size and biomass gasifier (5 kW) for solar (5 kW) - fuel cell (5 kW) and the optimal energy cost is around Rs 15,064/kWh,

According to simulation findings. Hybrid Optimization Renewable Energy Model (HOMER) is an abbreviation for Hybrid Optimization Renewable Energy Model. HOMER Pro compares the hourly electrical energy demand to the energy the system can offer at that hour and calculates the energy flows to and from each element of the system, simulating the functioning of the system by completing a one-year energy balance calculation for each hour.

Capital, replacement, operation, maintenance, fuel, and interest are all factored into system cost estimations. The biomass gasifier, solar energy, fuel cell, battery, and electrolysis simulation model was created for HOMER Pro software.[43]

This research looks into a possible method for replacing fossil fuel-based energy with a long-term solar energy source. The floating solar system and integrated hydrogen production unit are used to investigate the electrical energy requirements of a small settlement. The information comes from the Muscular Dam in Turkey's Aegean area.

The HOMER Pro program is used to analyze the results. Photovoltaic (PV) power supplies the needed load as well as extra power for the electrolyzer and hydrogen generation. Conserving land by preventing its usage in traditional PV farms, saving water by reducing evaporation, and compensating for the intermittent availability of solar electricity are only a few of the outcomes of the study for the investigated scenario. By generating power using the fuel cell, the hydrogen is used to counteract the electrical demand. The 3010 square meter shade area of the floating PV (FPV) system minimizes water evaporation of water resources. Without any grid connection or fossil fuel use, FPV and hydrogen systems provide 99.43 percent of power demand, with 60.30 MWh/year of the 211.94 MWh/year of energy produced by electrical load being used at $0.6124/kWh. levelized cost of electricity (LCOE).[44]

The goal of this article is to build an autonomous hybrid alternating current/direct current (AC/DC) microgrid for a community system that is located on an island with no access to the grid. It consists of photovoltaic (PV) arrays, a diesel generator, AC loads, and battery energy storage devices to ensure uninterruptible power supply during periods of low sunlight. In this residential application, a multi-objective, non-derivative optimization is examined; the primary goal is to reduce system costs while ensuring that no load shedding occurs.

Additionally, CO2 emissions are estimated to show the proposed system's environmental benefits. The commercial program HOMER Pro is used to find the most cost-effective design from hundreds of possibilities while also achieving the secondary goal. A sensitivity analysis is also carried out to assess design resilience in the face of fuel price and PV generation unpredictability.[45]

The major objective of this research is to estimate the minimal cost of energy (COE) for five distinct worldwide regions based on renewable energy systems: Squamish, Canada; Los Angeles and Golden, USA; and Brisbane and Adelaide, Australia. This was accomplished by looking into power generation and hydrogen synthesis using renewable energy sources (mostly solar and wind) in order to create synthetic fuels by collecting CO2 from the atmosphere. Photovoltaic

(PV), wind turbines (WT), and combinations thereof, as well as battery banks and hydrogen technologies, are examined in nine distinct renewable energy systems.

The microgrid software "Hybrid Optimization Model for Multiple Energy Resources" (HOMER Pro) was used to simulate the optimal size of system equipment's and to find the most cost-effective configurations for specific sites. The results reveal the integration of PV, WT, a battery bank, an electrolyzer, and a hydrogen tank at Golden, Colorado, USA is at 0.50 $/kWh while considering minimal COE. At the same site, it was discovered that without a battery bank, the minimum COE is 0.78 $/kWh. The cost rise in this scenario is because of the increased capital costs of system equipment, primarily hydrogen technology. The findings of this study show that for long-term energy storage in off-grid energy systems, hydrogen has a cost advantage over batteries.[46]

For stand-alone applications, a hydrogen fuel cell (HFC) and solar photovoltaic (SPV) hybrid renewable energy system (HRES) is proposed. This system, which include of a hydrogen tank, a battery, and an electrolyzer, is applied to store energy. The cost-effectiveness of applying HRES electricity to archive the electrical load conditions of an article facility in India is investigated. The strange theory program calculates the best capital value and equipment replacement cost and after is applied in HOMER pro software to find the perfect HRES performance. The output determined the HFC, and battery bank are related HRES modules for meeting load demand late at night and early in the morning [47].

2.3. Overview Electrolysis

Water is one of the most abundant and limitless raw elements on the planet, and it may be utilized to make H_2 through water-splitting techniques like electrolysis. The hydrogen generated will be the cleanest energy carrier for humanity if renewable energy sources provide the requisite energy input.

Electrolysis is the most successful approach for water splitting, which is a well-established and well-known process. However, because the reaction is particularly endothermic, electricity gives the required energy input. A stander electrolysis unit or electrolyzer, as shown in Fig.4, include of a cathode and an anode submerged in an electrolyte. When an electrical current is applied, water splits and hydrogen is created at the cathode. At the same time, oxygen is developed at the anode through the reaction [48]:

$$2H_2O \rightarrow 2H_2 + O_2$$

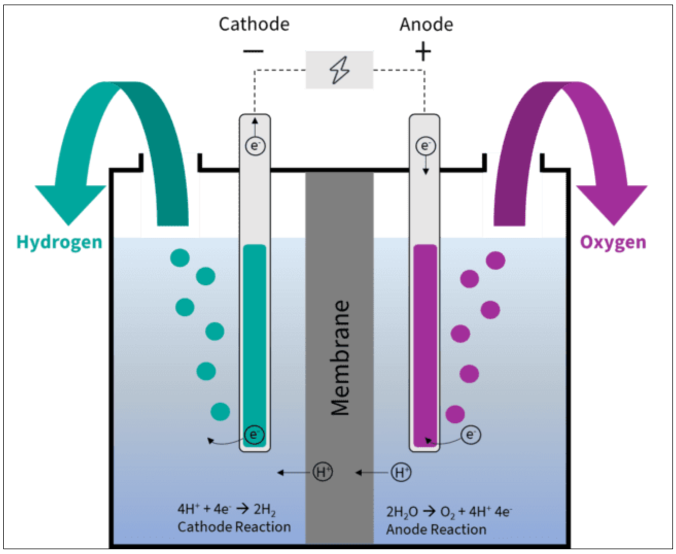

Figure 4 The fundamental of water electrolysis process.[48]

2.3.1. Types of Electrolyzers

Water electrolysis technology may be divided into three primary groups based on electrolyte utilized in the electrolysis cell.

Alkaline

Alkaline water electrolysis occurs at a low temperature (60–80 °C), with KOH and/or NaOH aqueous solution as the electrolyte, with the electrolyte concentration ranging from 20% to 30%. The diaphragm of an alkaline electrolyzer is made of asbestos, while the electrode is made of nickel materials. The produced hydrogen is nearly 99% pure; nevertheless, an alkali fog in the gas must be eliminated, which is commonly accomplished by desorption.[50]

PEM

The proton exchange membrane fuel cell technology underpins PEM electrolysis. Asbestos is replaced with proton exchange membranes, which transport protons across the membrane. A PEM's gas permeability is significantly lower than that of asbestos. PEM electrolyzers are more environmentally benign since the produced gas does not contain an alkaline fog. PEM electrolysis is also a potential hydrogen generation method because of its quick reaction, high efficiency, small design, and high output pressure.[50]

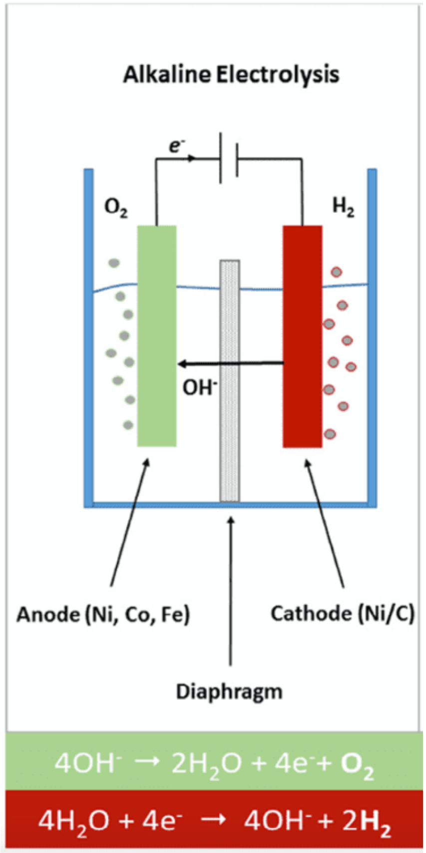

Figure 5 Operation principles of alkaline.[51]

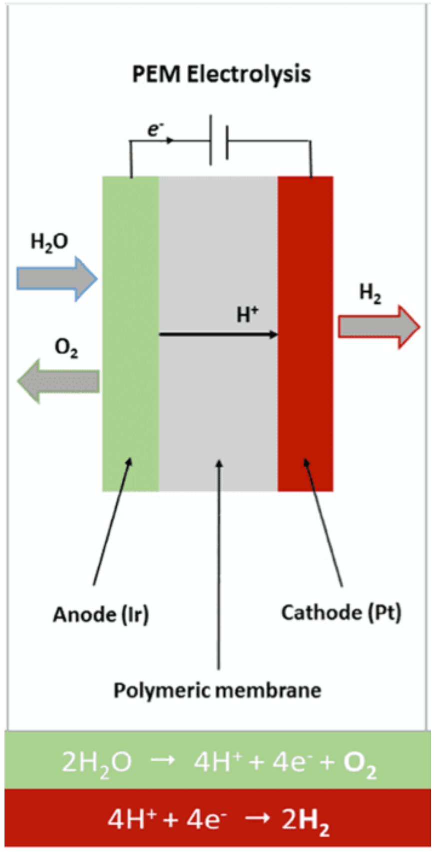

Figure 6 Operation principles of PEM.[51]

SOE

The energy efficiency of high-temperature Solid Oxide Electrolysis (SOE) is great; when heat utilization is factored in, the efficiency is above 90%. Anions transport at high temperature in the SOE using ZrO3 doped with 8mol percent Y2O3 as the electrolyte. Thermally and chemically, the solid oxide is a stable material. Water electrolysis necessitates a lower voltage at high temperatures, resulting in decreased energy usage. High-temperature water electrolysis has a thermal efficiency of 100%. [50]

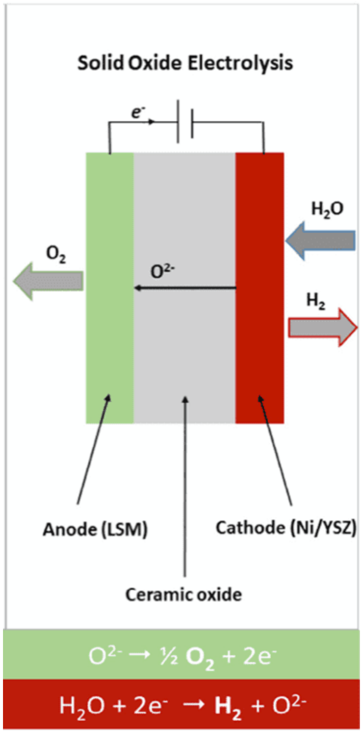

Figure 7 Operation principles of SOE.[51]

This table shows a comparison between the three types of electrolyzers:

Table 2 Comparsion of different types of electrolyzers.[51][52][53]

Compare item	**Alkaline**	**PEM**	**SOE**
Charge carrier	OH^-	H^+	O^{2-}
Temperature	20-80 °C	20-200 °C	500-1000 °C
Electrolyte	Liquid	Solid (Polymeric)	Solid (Ceramic)
Efficiency	60-75 %	70-90 %	85-100 %
Advantages	- Oldest and well-established technology - Cheapest and effective cost	- High current density - High voltage efficiency - High dynamic operation - High gas purity - Rapid system response	- Highest efficiency - High pressure operation
Disadvantages	- Low Current Density. - Degree of Purity is low(crossover of gases) - Electrolyte Liquid and Corrosive - Low dynamic operation	- New technology and partially established - High cost of components - Acidic environment - Limited and costly membrane	- Technology in laboratory phase - Durability is low due to high heat, Ceramics

From this table above, it was concluded that the PME type is the best among these types, and it is the one that was used in this research.

2.4. NEOM Green City

NEOM City (New Future) is a city in Saudi Arabia's Tabuk Province, in the northwest. It is located in latitude 29 N and longitude 35 E, as seen in Figure 8.

Figure 8 Position of NEOM city [48]

NEOM is situated a long distance from the est utility grid connection point. NEOM's destination is distinguished by a elevated average scale of sun irradiation. The daily horizontal solar radiation averages roughly 5.85 kWh/m2. Figure 9 [49] depicts the annual mean daily solar radiation and clearance index. In June, the greatest daily irradiance value of 8.085 kWh/m2/d is recorded. In contrast, December has the lowest daily irradiance of 3.542 kWh/m2/d.

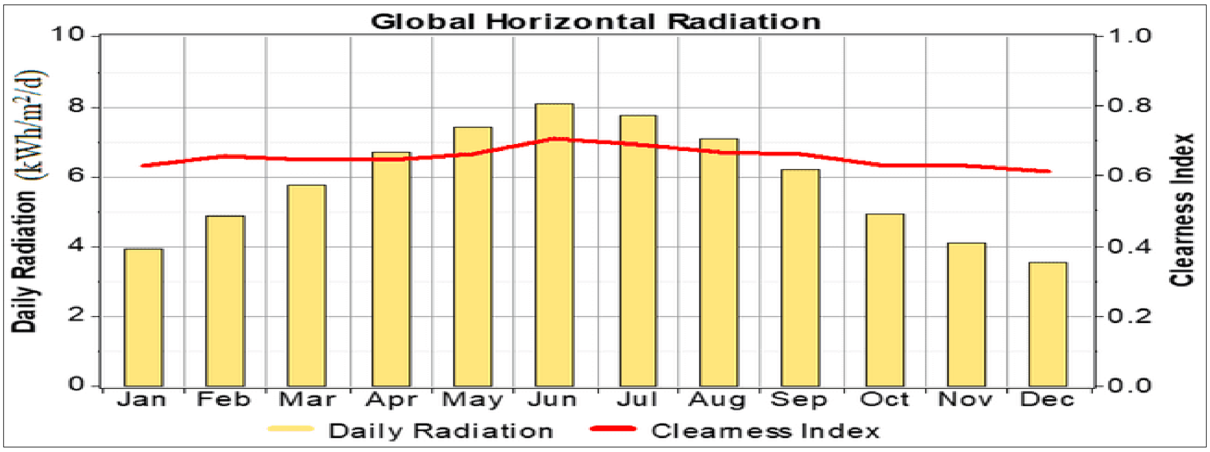

Figure 9 Mean daily solar radiation level and clearance index during the year.

It is intended to include smart city technology while simultaneously serving as a tourist attraction. It will span 460 kilometers along the Red Sea coast and encompass a total area of 26,500 km2. The cost is anticipated to be $500 billion. More than a million people will call it home and work [50-51]. NEOM City will serve as a paradigm for living, working, and succeeding in a sustainable manner. It will be entirely powered by renewable energy (RE). This presents a significant issue due to the intermittent and unpredictable nature of solar and wind resources, etc., necessitating massive energy storage to feed a stable grid [52–53].

NEOM is the name of the project, and it runs along the Red Sea Coast and the Gulf of Aqaba. It is the first initiative to link Asia, Africa, and Europe. It's Vision 2030, a vision of a more sustainable future and a new evolutionary way of living.

3. Methodology

3.1. NEOM city: location and potential

Neom is a town in Saudi Arabia's Tabuk Province in the northwest. It will include smart town technology and provide as a tourist attraction. The location is north of the Red Sea, east of Egypt across the Tiran Strait, and south Jordan. It will encompass 26,500 km2 and stretch 460 kilometers along the Red Sea's coast, Figure 10. shows the monthly average

Global Solar Horizontal Irradiance (GHI) data in NEOM city obtained from the HOMER Pro program and Figure 11. shows the Global Horizontal Radiation in Saudi Arabia.

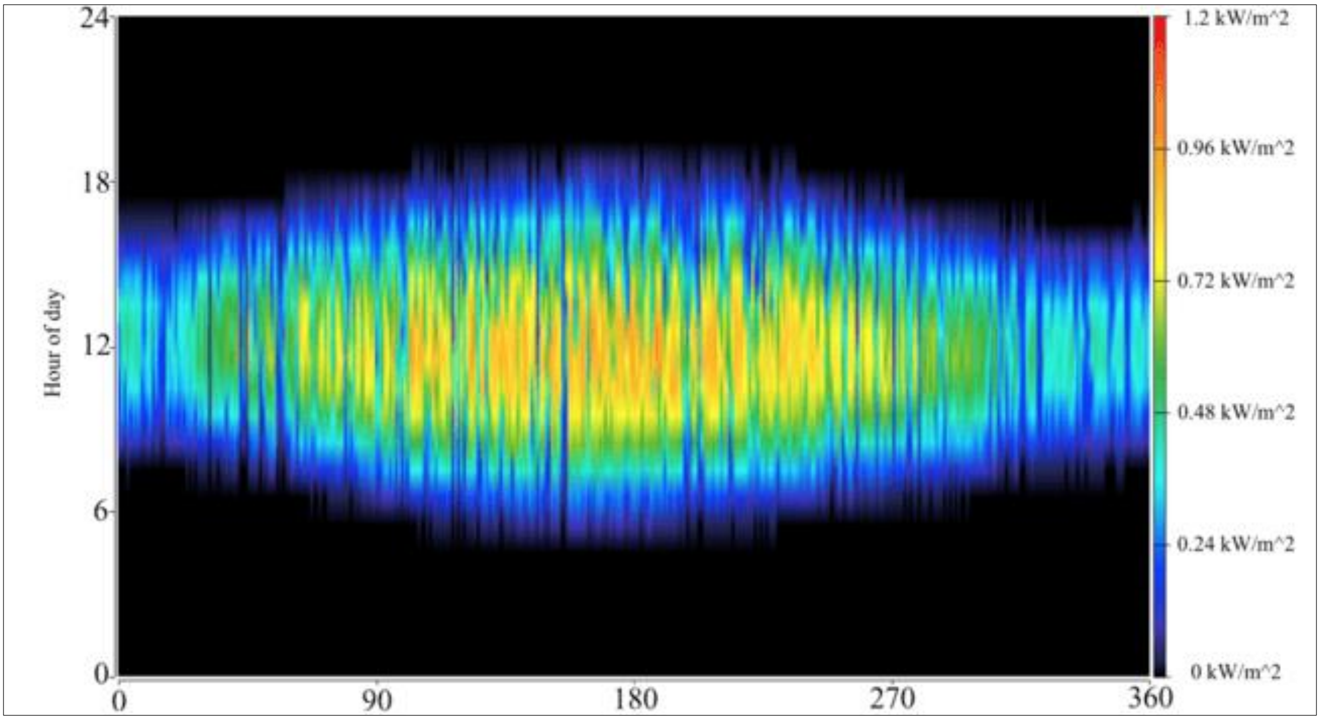

Figure 10 Data map for Global Solar Horizontal Irradiance (GHI) in NEOM city

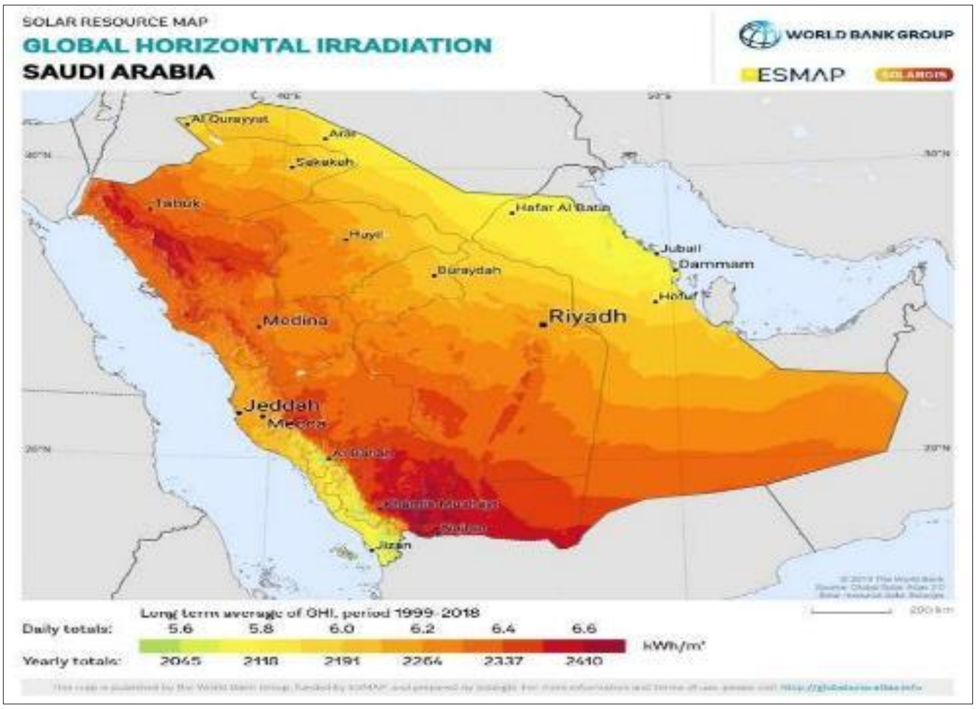

Figure 11 Global Horizontal Irradiation of Saudi Arabia

3.2. System Design

The main advantage of using renewable energy is to combine many sources to produce green hydrogen, the hybrid system used PV cells and an electrolyzer to gain hydrogen. This method used solar energy due to the availability of the sun in Saudi Arabia because the Kingdom occurs in the sunbelt zone which gives the country strong sun radiation. Once the water passes through the electrolyzer, the electrolyzer separates the oxygen from the hydrogen to gain pure hydrogen in the storage tank. The below flow chart at Figure.12 explains the methodology of this research, Figure.13 shows the schematics of the components of the system that will be studied in the HOMER Pro program.

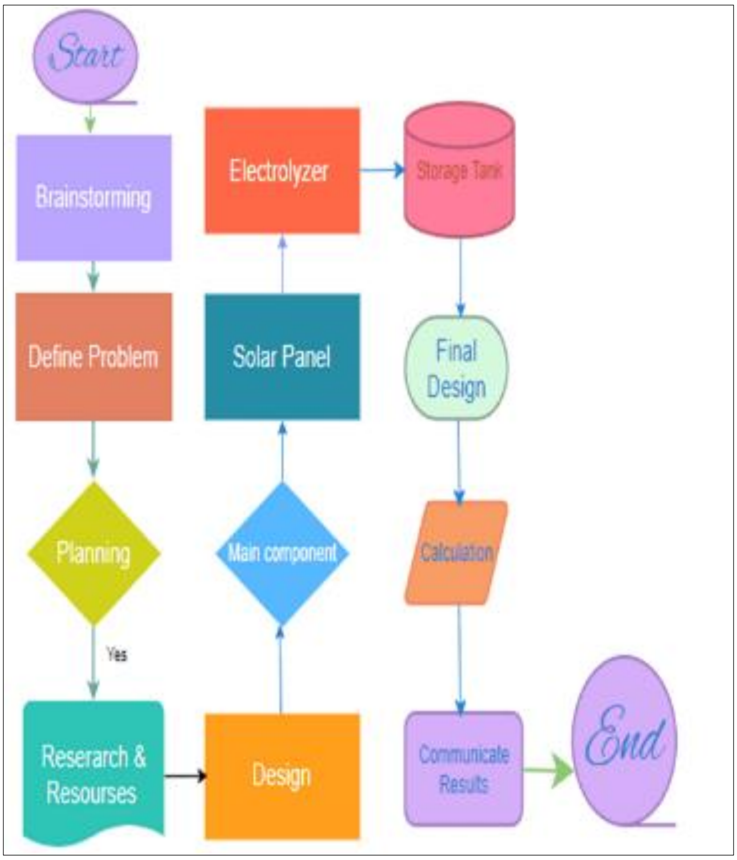

Figure 12 Flow chart of research

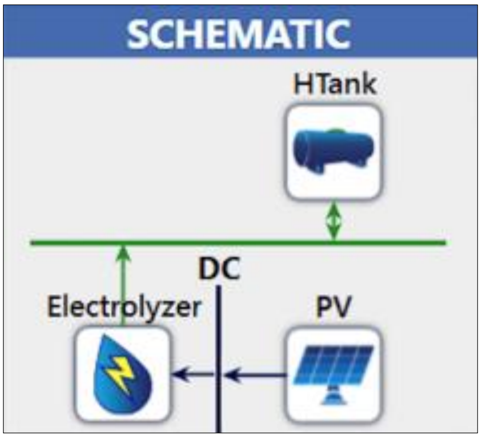

Figure 13 Schematics of the system components

3.2.1. Photovoltaic array

The solar panel was selected from the type CAT® Photovoltaic Module PVT1157.5 and the following table shows the most important specifications of this panel

Table 3 The characteristics for the PV solar panel

Items	**Value**
Weight	12 kg
Voltage at PMAX	71.2 V
Current at PMAX	1.65 A
Nominal Power (± 5%)	117.5 W
Module Efficiency	16.32 %
Dimension	1200 * 600 mm

Figure 14 CAT® Photovoltaic Module PVT1157.5

3.3. Measure the space between each PV

A measurement was made of the required distance between each solar panel to achieve the best performance, and then all calculations were made for every 100 m² in the city of NEOM to facilitate the calculation of any other space as needed.

- The space between the panels (*d*):

$$d = \frac{\sin(180 - (\alpha + \beta)) * Y}{\sin \alpha}$$

Where:

α = Elevation Angle
β = Tilted Angle
Y = Length of the Panel = 1.2 m

To calculate Elevation Angle (α):

$$\alpha = 90 - \varphi + \delta$$

Where:

φ = Latitude of NEOM = 28.143°

δ = Declination angle at 21th of June = 23.5°

then:

$$\alpha = 90 - 28.143 + 23.5 = 38.357°$$

To calculate Tilted Angle (β):

$$\beta = 90 - \alpha = 90 - 38.357 = 51.643°$$

The nearest β stander design = 60°

Then:

$$d = \frac{\sin(180 - (38.357 + 60)) * 1.2}{\sin(38.357)} = 1.9\, m$$

- Now the number of possible solar panels will be calculated per 100 m^2:

$$Number\ of\ panels = \frac{Total\ panels\ area}{Single\ panle\ area}$$

Where:

Total panels area = 100 m^2

$$Single\ panel\ area = panel\ width * d$$

$$Single\ panel\ area = 0.6\, m * 1.9\, m = 1.4\, m^2$$

Then:

$$Number\ of\ panels = \frac{100\, m^2}{1.14\, m^2} = 87.7 = 87\ panels$$

- To calculate the total number of solar systems:

$$Total\ Power\ of\ solar\ system = Number\ of\ panel * P(mpp)\ for\ panel$$

$$Total\ Power\ of\ solar\ system = 87 * 117.5\, W = 10.22\, kW$$

The total output power of solar system is 10.22 kW

3.3.1. Electrolyzer

The selected electrolyzer is QL-2000 PEM electrolyzer as shown in below. As well as figure 15 showing the electrolyzer.

Table 4 The characteristics of the Electrolyzer

Item	Value
Output Flow Rate	0-2020 ml/min
Output Pressure	0.4 MPa
Purity of Hydrogen	>99.999 %
Input Power	>1000 W
Dimension (L x W x H)	505*360*352 mm
Net Weight	>30 kg

Figure 15 QL-2000 Electrolyzer

3.4. Hydrogen Tank storage

The hydrogen molecule H_2 exists in various forms, depicted in the phase diagram, depending on temperature and pressure (Fig. 16). At low temperatures, hydrogen is a solid with a density of 70.6 kg/m^3 at 262°C and a density of 0.089886 kg/m^3 at 0°C and a pressure of 1 bar. At increased temperatures, hydrogen is a gas with a density of 0.089886 kg/m^3 at 0°C and a pressure of 1 bar.

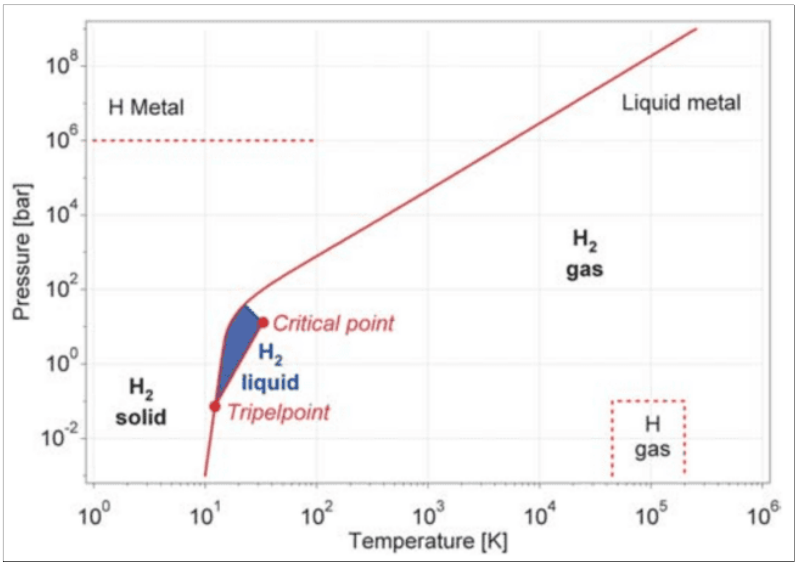

Figure 16 Primitive phase diagram for hydrogen. [54]

Hydrogen is stored in hydride or molecular hydrogen in hydrogen storage materials. The hydrides contain hydrogen atoms: protide (hydride) H, protium H0, and proton Hþ. In addition, boron and aluminum create negative charged molecular hydrides (BeH, AleH).[53] This table represent a comparison between the many kinds of hydrogen storage [55]:

Table 5 Comparison between the different types of hydrogen storage [56]

Parameters	Compressed Storage	Liquid Storage	Chemical Storage	Physisorption
Gravimetric Capacity ρm	13 wt %	Varies	<18 wt %	20 wt %
Volumetric Capacity ρv	<40 kg/m3	70.8 kg/m3	150 kg/m3	20 kg/m3
Temperature	273 K	21.5 K	573-373 K	Varies
Pressure	800 bars	1 bar	1 bar	100 bars
Method of Storage	Compressed gas storage	Cryogenic storage	Chemical storage	Physical adsorption by porous materials
Benefits	Lightweight, highly benefi-cial for fuel purpose, occu-pies smaller space and energy effective	Volumetrically and gravimetrically efficient, long term hydrogen storage	High storage density and low reactivity and short storage time	Fully reversible process, no accumulation of impurities, fast cycle life and refilling time
Limitations	Requires high-pressure cylinder, volumetrically and gravimetrically inefficient	Requires compressed tanks, suffers from large energy loss due to liquefaction and boil off process and high tank cost	Reacts violently with moist air, cumber-some to handle, ab-sorption of impuri-ties, lack of reversi-bility, desorption at elevated temperature and slow kinetics of dehydrogenation	Clustering problem, requires low temperature or exceedingly high pressure and shows weak interaction with the H2 molecule

4. Results and Discussion

The simulation was carried out using the HOMER Pro program version 3.14.7880.21077.

4.1. PV Panels

When making a simulation of the solar panels used, which are a type of CAT 117.5W, whose data were mentioned in the previous section, we find a summary of these results in the following table, knowing that all the results were calculated per 100 m^2 for ease of comparing and understanding the results.

Table 6 PV Statistics

Quantity	Value	
Mean Output	53.5	kWh/d
Capacity Factor	21.8	%
Hours of Operation	4,279	hr/yr

The capacity factor is the ratio of the annual average energy generation (kWh) of an energy installation plant separated by the theoretical maximum annual energy output of a plant, considering it operates at its peak estimated capacity every hour of the year.

Figure 17 present the data map (D-map) of the production of electricity from solar energy per hour on all days of the year:

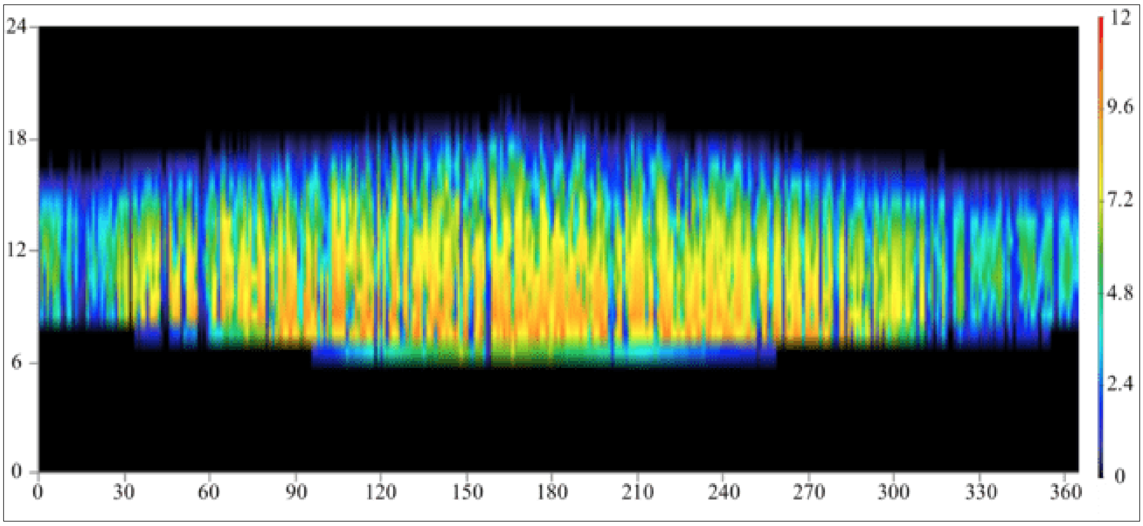

Figure 17 D-map for PV Output

The following figure shows the monthly average production of electricity from solar panels:

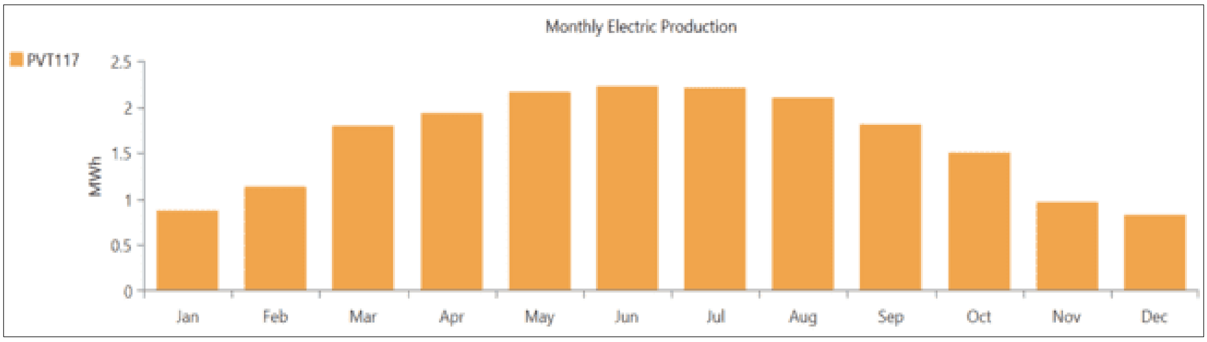

Figure 18 PV monthly electrical production

4.2. Electrolyzer

The electrolyzer was of the PEM type, of the QL-2000 brand, and the most important results were as mentioned in the table below:

Table 7 Electrolyzer statistics

Quantity	Value	
Maximum output	0.215	kg/hr
Mean Output	0.0480	kg/hr
Capacity Factor	22.3	%
Hours of Operation	4,279	hr/yr
Specific consumption	46.4	kWh/kg
Total Production	420	kg/yr

Figure. 19 shows the data map of hydrogen production from the electrolyzer per hour in all days of the year:

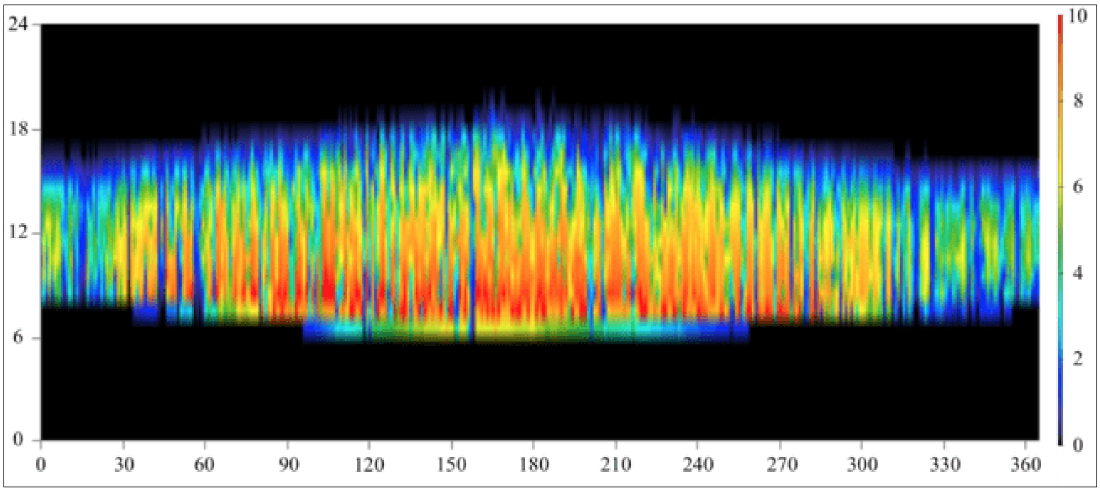

Figure 19 D-map for Electrolyzer Output

4.3. Hydrogen Tank

The table and the following figure show the most important details in the hydrogen tank after it was produced from the electrolyzer and stored:

Table 8 Hydrogen Storage Tank details

Quantity	Value	
Hydrogen storage capacity	450	kg
Content at beginning of year	0	kg
Content at end of year	420	kg
Energy storage capacity	15,000	kWh
Actual Energy stored	14,000	kWh

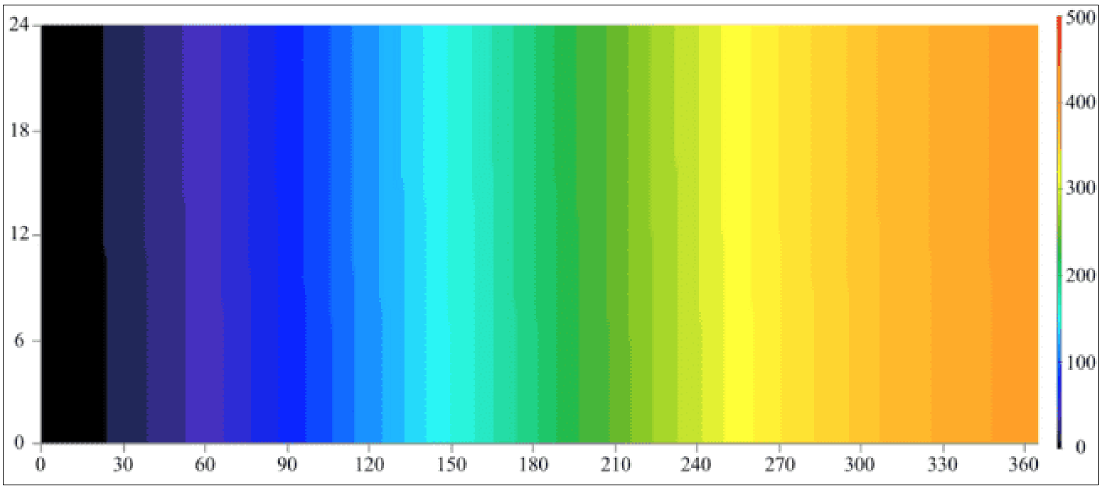

Figure 20 D-map for Hydrogen Stored

4.4. The potential of hydrogen production in several cities in KSA

A comparison was made in the ability to produce hydrogen in several cities in the Kingdom of Saudi Arabia, namely: NEOM, Taif, Riyadh, Dammam, Sakaka and Najran, and the results were as follows:

Table 9 Cities Comparsion of Hydrogen Prodction

City	Mean PV output	Total Electricity Production	Total Hydrogen Production
NEOM	53.5 kWh/d	19,530 kWh/yr	420 kg
Taif	50.7 kWh/d	18,494 kWh/yr	398 kg
Riyadh	51.0 kWh/d	18,633 kWh/yr	401 kg
Dammam	51.3 kWh/d	18,737 kWh/yr	404 kg
Sakaka	54.0 kWh/d	19,724 kWh/yr	425 kg
Najran	50.0 kWh/d	18,259 kWh/yr	393 kg

From this table, it can be concluded that NEOM city is considered one of the highest cities in the Kingdom with high efficiency in solar energy production.

4.5. Hydrogen Economic viability, Prospects and Obstacles

Hydrogen has been identified as the most environmentally friendly and promising energy source for the twenty-first century. Furthermore, it is an essential chemical raw material that is universally employed in industries. Nowadays, a wide range of viable hydrogen generation processes has been established, including the reforming/oxidation/gasification of fossil fuels, the breakdown of hydrogen-including materials, water electrolysis, and so on [38]. Aside from the significant rise in hydrogen consumption, the market shows a hard trend across diversification of the hydrogen- generation measurement. This encourages the growth of novel hydrogen-production technologies (such as photocatalytic water separation, solar energy water separation, and so on) [39]. Even thou these technologies are not yet established enough to exchange current commercial hydrogen-production systems, they provide huge room for progress in the long run. Future research should develop green, efficient, convenient, safe, and low-cost hydrogen-generation methods [40]. Table 10 summarizes several approaches' capital and hydrogen costs, using data from Ref. [41]. Each technology must be assessed using specific broad indicators, like the clarity index and life cycle cost while considering the method, economy, and environment [42,43]. It is especially critical to conduct an impartial comparison analysis of various technologies to give technical guidance for the healthy growth of the hydrogen-production business.

Table 10 Comparison of the capital costs and hydrogen costs of various hydrogen-production methods[44].

Process	Energy source	Feedstock	Capital cost M$	Hydrogen cost $/kg
Steam methane reforming	Fossil fuels	Natural gas	180.7 to 226.4	2.08 to 2.27
Coal gasification	Fossil fuels	Coal	435.9 to 545.6	1.34 to 1.63
Autothermal reforming of methane	Fossil fuels	Natural gas	183.8	1.48
Methane pyrolysis	Internally generated steam	Natural gas	–	1.59 to 1.70
Biomass pyrolysis	Internally generated steam	Woody biomass	3.1 to 53.4	1.25 to 2.20
Biomass gasification	Internally generated steam	Woody biomass	6.4 to 149.3	1.77 to 2.05
Direct bio-photolysis	Solar	Water + algae	50 $/m2	2.13

Indirect bio-photolysis	Solar	Water + algae	135 $/m2	1.42
Dark fermentation	Organic biomass	––	––	2.57
Photo fermentation	Solar	Organic biomass	–	2.83
Solar photovoltaic electrolysis	Solar	Water	12.0 to 54.5	5.78 to 23.27
Solar thermal electrolysis	Solar	Water	22.1 to 421.0	5.10 to 10.49
Wind electrolysis	Wind	Water	499.6 to 504.8	5.89 to 6.03
Nuclear electrolysis	Nuclear	Water	–	4.15 to 7.00
Nuclear thermolysis	Nuclear	Water	39.6 to 2107.6	2.17 to 2.63
Solar thermolysis	Solar	Water	5.7 to 16.0	7.89 to 8.40
Photoelectrolysis	Solar	Water	–	10.36

Even though more than 90% of the world's hydrogen is produced from advanced, low-cost methane and other gaseous fossil hydrocarbon fuels, the subsequent compression, storage, transportation, and distribution of the technology will inevitably result in a steady rise in the selling amount to users [45]. Furthermore, much fundamental support facilities are insufficient, and technologies are incapable of meeting the criteria for small-scale deployment of hydrogen sources in power supply and other industries [46].

5. Conclusion

After addressing the results, the results proved that the method of producing hydrogen is 100 % renewable and has no side effect to the environment. The solar radiation in NEOM city was able to produce the required amount for our project. The solar panel gave 420 kg/yr of total production of green hydrogen. The PEM electrolyzer was the perfect selection for the project. The electrolyzer separated the hydrogen from oxygen without any difficulties. The hydrogen storage tank had a 450kg capacity, which is enough to store the hydrogen gas, and NEOM city is suitable for solar hydrogen production as shown in the solar characteristics.

Appendix

A- Engineering Standards for solar photovoltaic systems according to Saudi electricity company:

PV MODULES

• SASO IEC 61215-1:2017 – Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1: Test requirements.

• SASO IEC 61215-1-1:2017 – Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules.

• SASO IEC 61215-1-2:2017 – Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules.

• SASO IEC 61215-1-3:2017 – Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-3: Special requirements for testing of thin-film amorphous silicon based photovoltaic (PV) modules.

• SASO IEC 61215-1-4:2017 – Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-4: Special requirements for testing of thin-film Cu (In,GA)(S,Se)2 based photovoltaic (PV) modules.

• SASO IEC 61215-2:2017 – Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 2: Test procedures.

• SASO IEC 61730-1:2017 – Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction.

• SASO IEC 61730-2:2017 – Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing.

• SASO IEC 61701:2014 – Salt mist corrosion testing of photovoltaic (PV) modules.

• SASO IEC TS 62804-1:2017 – Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 1: Crystalline silicon.

• SASO IEC 62716:2016 – Photovoltaic (PV) modules - Ammonia corrosion testing.

• SASO IEC 62759-1:2015 – Photovoltaic (PV) modules - Transportation testing - Part 1: Transportation and shipping of module package units.

• SASO IEC 62790:2015 – Junction boxes for photovoltaic modules - Safety requirements and tests.

• SASO IEC 62852:2015 – Connectors for DC-application in photovoltaic systems - Safety requirements and tests.

• SASO IEC 62979:2018 – Photovoltaic modules - Bypass diode - Thermal runaway test. TECHNICAL STANDARDS FOR THE CONNECTION OF SMALL-SCALE SOLAR PV SYSTEMS Page 44/44

• SASO IEC TS 62941:2017 – Terrestrial photovoltaic (PV) modules - Guideline for increased confidence in PV module design qualification and type approval.

• SASO IEC TS 62782:2017 – Photovoltaic (PV) modules - Cyclic (dynamic) mechanical load testing.

• IEC 60068-2-68:1994 – Environmental testing - Part 2-68: Tests - Test L: Dust and sand.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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