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Advancing Green Hydrogen Production in Saudi Arabia: Harnessing Solar Energy and Seawater Electrolysis

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ABSTRACT: The transition to clean and sustainable energy sources is crucial for combating the challenges posed by climate change. Green hydrogen, produced through renewable energy-driven electrolysis, holds significant promise as a viable clean energy carrier. The study introduces a system that leverages abundant solar energy and utilizes seawater as the feedstock for electrolysis, potentially offering a cost-effective solution. A comprehensive mathematical model, implemented in MATLAB, is employed to simulate the design and operational efficiency of the proposed green hydrogen production system. The system's core components include solar panels as a clean energy source, an advanced MPPT charge controller ensuring optimal power delivery to the electrolyzer, and a seawater tank serving as the electrolyte source. The model combines these elements, allowing for continuous operation and efficient hydrogen production, addressing concerns about energy losses and cost-effectiveness. Results demonstrate the influence of solar irradiance on the system's performance, revealing the need to account for seasonal variations when designing green hydrogen production facilities. Theoretical experiments are conducted to evaluate the behavior of a lithium battery, essential for stabilizing the system's output and ensuring continuous operation during periods of low solar radiation.

Keywords: Solar energy; PV; Green hydrogen; Seawater electrolysis

1. Introduction

In 2022, for Saudi Arabia, the total electrical energy production increased by 0.77% in 2020 with the quantity of production that reached 338,031 GWh compared to 335,445 GWh in 2019. Electrical energy consumption also increased by 0.21% during 2020 to reach 289,333 GWh, compared to 288,713 GWh in 2019 [1]. Despite this, global reliance on fossil fuels poses several challenges, including environmental degradation, resource security, and sustainability concerns. Traditional energy sources may have a lower initial cost but lack long-term sustainability. In light of the International Energy Agency's projection of a 25% to 30% increase in global energy consumption by 2040, there is a pressing need to transition towards cleaner and more sustainable energy alternatives.

Green hydrogen emerges as a promising solution, with water electrolysis being the key process to generate hydrogen and oxygen. Various industries, such as chemical, petrochemical, and metallurgical sectors, use hydrogen heavily, contributing to significant carbon emissions. Utilizing green hydrogen as a raw material can pave the way for decarbonization in these sectors, including emissions-free steel production. Additionally, green hydrogen's voluminous and long-lasting energy storage potential could provide renewable reserves for the electrical grid and meet high-temperature energy demands.

In the transportation sector, green hydrogen holds great promise. It can replace highly polluting fuels in long-haul and air transportation, offering a clean alternative for marine and aviation industries. Furthermore, green hydrogen is crucial for the transportation of large goods by road and rail. Despite its potential, the adoption of green hydrogen fuel-cell cars in the automotive industry is yet to make a substantial impact.

Overall, green hydrogen represents a viable solution to address the challenges of traditional energy sources and decarbonize various sectors, driving a shift towards a cleaner, more sustainable energy future.

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2. Literature Review

Based on a multitude of research studies, the transition from conventional energy sources to renewable alternatives is seen as a critical step in addressing the challenges associated with green hydrogen deployment. This transition is expected to alleviate cost constraints and promote the advancement of green hydrogen technology [2]. Research efforts have also been directed toward estimating the global production and supply costs of green hydrogen and hydrogen-based green energy products [3], optimizing the design of net-zero energy buildings with integrated green hydrogen production and energy storage systems, taking into account environmental factors [4], as well as developing process models for alkaline water electrolyzers [5]. Additionally, there has been substantial work on modeling and controlling hydrogen production systems based on electrolysis processes.

2.1. History and Background

Hydrogen's discovery dates back to 1766, and in 1783, it was used in balloons for the first time. The introduction of hydrogen-powered cars took place in 1972; however, their adoption was limited due to the availability of more affordable energy alternatives. Unlike primary energy sources such as petroleum, coal, and natural gas, hydrogen is considered an energy carrier or secondary energy source. It occurs in nature as combined molecules and requires energy input to obtain pure hydrogen.

When hydrogen reacts with oxygen, it forms water, making hydrogen energy often regarded as a clean energy option. However, its environmental impact depends on the manufacturing process. If fossil fuels like coal and petroleum are used in its production, hydrogen cannot be considered entirely clean. Only when produced using renewable energy sources like solar, wind, or water power can hydrogen be labeled as clean energy.

Hydrogen is categorized based on its production process. Grey hydrogen generates carbon dioxide (CO_2) emissions, blue hydrogen captures and stores CO_2, and green hydrogen is produced through water electrolysis using renewable energy sources. The distinction between these types of hydrogen helps identify their environmental impact and their contribution to cleaner energy systems.

2.2. Green Hydrogen Production

The opportunity to utilize hydrogen's potential contribution to a sustainable energy system has never been better. Only France, Japan and Korea had hydrogen use plans in 2019 when the IEA released its seminal report *The Future of Hydrogen for the G20*. More than 20 countries have publicly stated they are trying to establish strategies, 17 governments have published their hydrogen strategies, and countless businesses are looking to capitalize on the business potential presented by hydrogen [6]. These initiatives are necessary because a net-zero emissions energy system will require hydrogen. The NEOM Green Hydrogen Project, the largest utility-scale, commercial-based hydrogen facility in the world fueled exclusively by renewable energy, is one of the key strategies Saudi Arabia is attempting to pursue [7].

The cost differential between low-carbon hydrogen and hydrogen produced from fossil sources is an important obstacle. In the majority of the world's regions, creating hydrogen from fossil fuels is currently the least expensive alternative. The levelized cost of producing hydrogen from natural gas ranges from USD 0.5 to USD 1.7 per kilogram (kg), depending on local gas costs. The levelized cost of production rises to about $1 to $2 per kilogram when CCUS technologies are used to cut CO_2 emissions from hydrogen synthesis. Hydrogen production with renewable electricity ranges from USD 3 to USD 8 per kg. Through technology innovation and expanded deployment, there is a great opportunity to reduce production costs.

The contributions made to modeling, optimizing, developing and improving the production of green hydrogen are presented and discussed in Table 1.

Table 1. Contributions made to modeling, optimizing, developing, and improving the production of green hydrogen.

Previous work	Methods Used	Contributions	Practical Implications
Advances, Opportunities and Challenges of Hydrogen and Oxygen Production from Seawater Electrolysis: An Electrocatalysis Perspective [8]	- Seawater electrolysis - Development of new electrocatalysts	- Developing renewable energy sources to replace fossil fuels - Developing new electrocatalysts for seawater electrolysis	- Developing new electrocatalysts for seawater electrolysis - Reducing greenhouse gas and particulate emissions
Green processes and sustainable materials for renewable energy production via water splitting [9]	- Renewable hydrogen production via water splitting - Photocatalytic seawater splitting and organic waste utilization	- Overview of renewable hydrogen production technologies - Review of innovative hydrogen production methods	- Development of green and sustainable energy sources - Utilization of renewable resources for hydrogen production
Green hydrogen production potential for Turkey with solar energy [10]	- Solar energy exploitation through photovoltaic cells - Electrolysers used: alkaline, PEM, and SOEs	- Development of a hydrogen map concept - Investigation of solar energy-based hydrogen production potential in Turkey	- Identification of cities with high hydrogen production potential - Consideration of solar energy for green hydrogen production

Table 1. Continued.

Previous work	Methods Used	Contributions	Practical Implications
Seawater electrolysis for hydrogen production: a solution looking for a problem? [11]	- Seawater reverse osmosis (SWRO) - Proton exchange membrane (PEM) electrolysis	- Critically assesses the research and development needs for direct seawater electrolysis - Analyzes the economic and environmental incentives of pursuing direct seawater electrolysis technology	- Limited economic and environmental incentives for direct seawater electrolysis - Need to realign research investments for decarbonization
Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis [12]	- Alkaline electrolysis - Proton-exchange membrane electrolysis	- Comprehensive review on hydrogen production technologies - Assessment of three leading electrolysis methods	- Development of reliable carbon-free hydrogen production solutions - Consideration of other types of electrolysis and materials
Energy-saving hydrogen production by chlorine-free hybrid seawater splitting coupling hydrazine degradation [6]	- Fabrication of NiCo@C/MXene/CF - Preparation of NiCo@C/CF (control sample)	- Chlorine-free hydrogen production by hybrid seawater splitting - Fast hydrazine degradation and removal of harmful pollutants	- Chlorine-free hydrogen production from seawater - Efficient conversion of ocean resources to hydrogen fuel
Two-step thermochemical electrolysis: An approach for green hydrogen production [13]	- Electrolysis - Thermochemical water splitting	- Novel and cost-efficient water splitting process - Lower cost of energy required for hydrogen production	- Novel water splitting process combining electrical and chemical potentials - Potential for lower cost of hydrogen production
Efficiency and stability of hydrogen production from seawater using solid oxide electrolysis cells [14]	- Solid oxide electrolysis - Seawater splitting	- Solid oxide electrolysis used to split untreated seawater - Excellent performance and stability in seawater splitting	- Solid oxide electrolysis cells can efficiently produce hydrogen from seawater - Long-term operation has no significant effect on the cell structure and composition
Tapping hydrogen fuel from the ocean: A review on photocatalytic, photoelectrochemical and electrolytic splitting of seawater [15]	- Direct seawater electrolysis - Photocatalytic and photoelectrochemical seawater splitting	- Comparison of light-driven and electrochemical seawater splitting technologies - Identification of promising advances in catalyst and process development	- Direct seawater electrolysis achieves high current densities. - Photocatalytic seawater splitting reduces adverse side-reactions.
Recent development in sustainable technologies for clean hydrogen evolution: Current scenario and future perspectives [16]	- Steam methane reforming (SMR), gasification, membrane reactor technologies, thermochemical processes, and solar energy technologies - Semiconductor-based photocatalytic water splitting	- Conventional and advanced hydrogen production technologies - Engineering strategies to enhance H_2 production	- Steam methane reforming (SMR), gasification, and membrane reactor technologies have potential for commercial-scale hydrogen production. - Semiconductor-based photocatalytic water splitting shows promise for enhancing hydrogen production.
Hydrogen Production by Water Electrolysis: Progress and Suggestions [17]	- Alkaline water electrolysis - Proton exchange membrane (PEM) water electrolysis	- Summarizes hydrogen demand, industry planning, and demonstrations - Analyzes alkaline and PEM water electrolysis technology	- Optimizing PEM electrolyzer performance and lowering equipment cost. - Proposal for green hydrogen generation and long-distance transportation.
Recent progress for hydrogen production by photocatalytic natural or simulated seawater splitting [18]	- Photocatalytic water splitting - Photocatalytic seawater splitting	- Recent advances in photocatalytic seawater splitting - Introduction of H_2 production photocatalysts and underlying mechanism	- Photocatalytic seawater splitting can alleviate freshwater resource limitations. - Current challenges and future potential advances discussed.
Sustainable hydrogen production [19]	- Photovoltaic-powered electrolysis - Solar photocatalytic hydrogen production from water	- Cooperative effort among multiple organizations - Evaluation of hydrogen production from photovoltaic-powered electrolysis	- Coordination of multiple agencies and successful results - Design, construction, and operation of hydrogen production facility
Latest progress in hydrogen production from solar water splitting via photocatalysis, photoelectrochemical, and photovoltaic-photoelectrochemical solutions [20]	- Particulate photocatalysis (PC) systems - Photoelectrochemical (PEC) systems - Photovoltaic-photoelectrochemical (PV-PEC) hybrid systems	- Photocatalytic water splitting with $SrTiO_3$:La, Rh/Au/$BiVO_4$:Mo photocatalyst - Photoelectrochemical water splitting on a tantalum nitride photoanode	- Solar-to-hydrogen conversion efficiency has exceeded 10%. - Photovoltaic-photoelectrochemical hybrid system reached 224% efficiency.
Advances in solar hydrogen production via two-step water-splitting thermochemical cycles based on metal redox reactions [20]	- Review of redox working materials and their comparisons - Assessment of solar chemical reactor designs and general evaluation	- Hydrogen energy can help solve greenhouse gas emissions. - ZnO/Zn is a potential candidate for two-step thermochemical water splitting.	- Development of a reactor for simultaneous synthesis and hydrolysis of metal/oxide nanoparticles - Investigation of redox pairs for solar hydrogen production
Energy futures and green hydrogen production: Is Saudi Arabia trend? [21]	-Investigated global trends and best practices in hydrogen energy adoption and investment. - Evaluated readiness and potential obstacles for hydrogen energy adoption.	- Investigated potential for hydrogen energy in Saudi Arabia - Provided policy implications and recommendations for energy industry	- Potential for green hydrogen production in Saudi Arabia - Challenges and obstacles for hydrogen energy adoption

Table 1. Continued.

Previous work	Methods Used	Contributions	Practical Implications
Potential of solar hydrogen production by water electrolysis in the NEOM green city of Saudi Arabia [22]	- Solar hydrogen production using solar energy - Hybrid system with different sources of renewable energy	- Solar hydrogen as a leading candidate for renewable energy - NEOM city in Saudi Arabia has high potential for green hydrogen production	- Solar hydrogen production is a promising renewable energy source. - NEOM city in Saudi Arabia has high potential for green hydrogen production.
Advancing direct seawater electrocatalysis for green and affordable hydrogen [23]	- Direct electrolysis of seawater using marine energy - Optimization of direct seawater splitting	- Analyzing barriers to optimizing direct seawater splitting - Identifying critical factors for efficient direct seawater electrolysis	- Direct seawater electrolysis can generate green hydrogen. - Development of low-cost electrolyzers is crucial.
Hydrogen production from seawater using H_2SO_4 catalyst by photovoltaic-electrolysis method [24]	- Seawater electrolysis method - Photovoltaic-electrolysis method	- Seawater electrolysis method for hydrogen production - Effect of voltage on electrolysis process	- Seawater electrolysis can be used for hydrogen production. - Higher voltage leads to increased hydrogen gas flow rate.
Large-scale green hydrogen production using alkaline water electrolysis based on seasonal solar radiation [25]	- Techno-economic analysis for green hydrogen generation - Genetic algorithm for determining optimal system size	- Techno-economic analysis for green hydrogen generation - Carbon footprint study to estimate CO_2 emissions	- Techno-economic analysis for green hydrogen production - Determination of optimal size and cost minimization strategies
Large-scale green hydrogen production via alkaline water electrolysis using solar and wind energy [26]	- Comparison of wind and solar solutions - Carbon footprint study and performance assessment technique	- Comparison of wind and solar solutions for large-scale green hydrogen production - Standardizing performance assessment technique for renewable-based hydrogen production systems	- Optimum electrolyser capacity for wind and solar energy - Easily adaptable for large-scale applications and environmental conditions

3. Problem Statement

The widespread adoption of green hydrogen as a viable solution to expedite the energy transition in Saudi Arabia is impeded by several social, economic, and technical challenges. Critical obstacles must be addressed before green hydrogen can be effectively produced and utilized in the country.

During the process of electrolyzing, liquefying, converting to other carriers, transporting and utilizing green hydrogen in fuel cells, a significant amount of energy is lost. Efficient electrolyzers that can compete with end-use electrification are necessary for green hydrogen to serve as a feasible fuel option. Failure to mitigate these losses may lead to a heavy reliance on naturally generated energy sources, hindering the transition to clean energy.

The transportation and storage of hydrogen pose considerable difficulties, requiring high-pressure containment and liquefaction at extremely low temperatures. Additionally, hydrogen's properties can cause pipeline steel to become brittle and increase the risk of faster leaks compared to natural gas or propane systems. Ensuring extremely high purity levels, up to 99.999%, is essential for hydrogen to operate fuel cells effectively.

Presently, the cost of green hydrogen production is relatively high, ranging between 6–12 USD per kilogram, making it economically prohibitive for widespread adoption. Addressing these challenges is crucial to unlock the potential of green hydrogen as an environmentally sustainable and economically viable energy solution in Saudi Arabia.

4. Materials and Methods

The research methodology employed in this article focuses on the development and evaluation of a green hydrogen production system using solar energy and seawater as the electrolysis feedstock. The study encompasses theoretical modeling to simulate the system's design and efficiency.

- Conceptual Framework:

The research begins with a conceptual framework outlining the components and functionalities of the proposed green hydrogen production system. The system's core components include solar panels, an advanced Maximum Power Point (MPPT) charge controller, an electrolyzer, a battery, and a seawater tank. The interconnections and interactions among these components are defined to create a comprehensive system design.

- Mathematical Modeling:

Mathematical modeling is carried out using MATLAB and Simulink to simulate the behavior of each component within the system. Models are developed for the Photo-Voltic's (PV) arrays, MPPT charge controller, battery, and electrolyzer, considering their characteristic equations and responses. The interactions between these models are integrated to create a holistic simulation of the entire green hydrogen production system.

- Data Collection and Analysis:

Data from the mathematical model is solved using Simulink/Matlab software, and analyzed to identify the system's performance. The impact of solar irradiance variations on the system's performance is assessed to ensure optimal performance in different weather conditions.

- Evaluation of Green Hydrogen Production:

The study evaluates the green hydrogen production process under different scenarios, such as varying solar irradiance, system load, and electrolyzer capacity. The energy efficiency and losses during electrolysis are quantified to understand the overall energy balance and identify areas for improvement.

- Recommendations and Future Scope:

Based on the research findings, the article provides recommendations for enhancing the system's efficiency, reducing costs, and addressing technical challenges. Future scope for scaling up green hydrogen production in Saudi Arabia is discussed, taking into account advancements in renewable energy technologies and potential policy support.

5. Research Novelty

The research paper focuses on advancing green hydrogen production in Saudi Arabia by harnessing solar energy and seawater electrolysis. This approach offers a cost-effective solution for producing clean energy carriers.

The study introduces a comprehensive mathematical model implemented in MATLAB to simulate the design and operational efficiency of the proposed green hydrogen production system. This model combines solar panels as a clean energy source, an advanced MPPT charge controller, and a seawater tank as the electrolyte source.

The research addresses the challenges of energy losses during electrolysis and the relatively high cost of green hydrogen production. It provides recommendations for enhancing the system's efficiency, reducing costs, and addressing technical challenges.

The study also highlights the need to account for seasonal variations in solar irradiance when designing green hydrogen production facilities. Theoretical experiments are conducted to evaluate the behavior of a lithium battery for stabilizing the system's output during periods of low solar radiation.

By addressing the identified challenges and implementing the recommended solutions, the research represents a significant step towards advancing green hydrogen production in Saudi Arabia and contributing to a greener and more sustainable future.

6. System Description

The schematic diagram, Figure 1, shows a proposed green hydrogen production system. The system consists of the following components:

- Photovoltaic: This is the source of renewable energy that powers the system. The photovoltaic panels convert sunlight into electricity, which is used to power the electrolyzer. PV inclination angle is 25° and azimuth is 0° (oriented to south)
- Electrolyzer: This is the device that splits water into hydrogen and oxygen gas. The electricity from the photovoltaic generator is used to power the electrolyzer, which causes the water molecules to split into their constituent elements.
- Battery: The battery is used to store excess electric energy produced by the PV. The battery can then be used to provide a source of electricity when the photovoltaic is not producing enough electricity to power the electrolyzer, such as at night or during cloudy weather.
- Seawater tank: The seawater tank is used to store the seawater to continuously feed the electrolyzer.
- Charge controller: The charge controller is used to regulate the flow of electricity from the photovoltaic generator to the battery. This ensures that the PV works on the maximum power point and the battery is not overcharged or discharged too deeply.

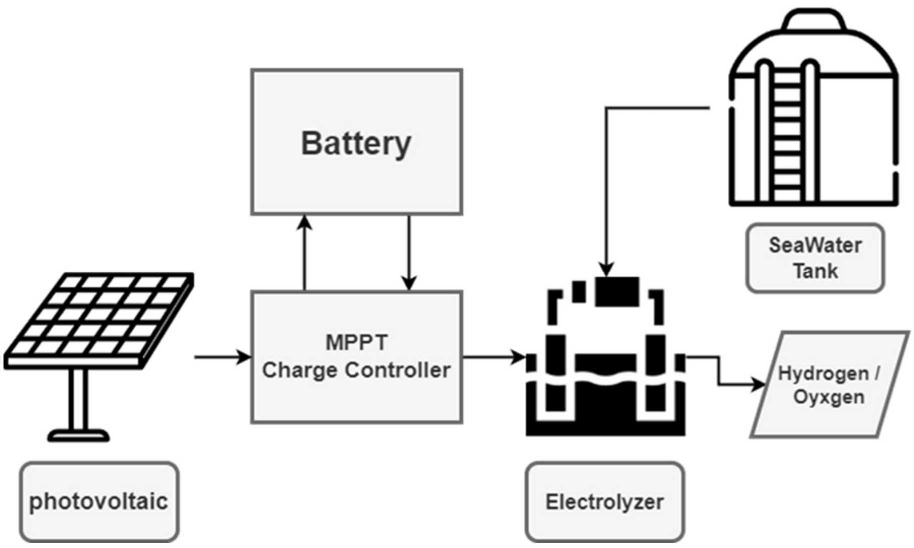

Figure 1. A schematic diagram of the proposed green hydrogen production system.

7. Mathematical Model

The components of the system, which include a solar panel, battery, MPPT controller, electrolyzer, and sea water tank, Simulation of developed mathematical models and analysis of various equations to create a system that can run continuously for 24 h and produce the greenest hydrogen for electrolysis. with the behavior of each component being described by mathematical equations. The mathematical model representation listed in Table 2.

Table 2. List of equation of the mathematical model.

Equation	No.
$I_0 = I_{rs} \cdot \left(\frac{T}{T_n}\right) \cdot \exp\left(\frac{q \cdot E_{g0} \cdot \left(\frac{1}{T_n} - \frac{1}{T}\right)}{n \cdot K}\right)$	1
$I_{RS} = \frac{I_{SC}}{e^{\left(\frac{qV_{oc}}{n \cdot N_s \cdot K \cdot T}\right)} - 1}$	2
$I_{sh} = \left(\frac{V + I \cdot R_s}{R_{sh}}\right)$	3
$I_{ph} = \left[I_{sc} + K_i \cdot (T - 298)\right] \cdot \frac{G}{1000}$	4
$I = I_{ph} - I_0 \cdot \left[\exp\left(\frac{q \cdot (V + I \cdot R_s)}{n \cdot K \cdot N_s \cdot T}\right) - 1\right] - I_{sh}$	5
$\frac{\partial P}{\partial V} = 0 \text{ for } V = V_{mp}$	6
$\frac{\partial P}{\partial V} = 0 \text{ for } V < V_{mp}$	7
$\frac{\partial P}{\partial V} = 0 \text{ for } V > V_{mp}$	8
$A = Ah \cdot 10\%$	9
$T = \frac{Ah}{A}$	10
$Q = Ah \cdot V$	11
$V_{cell} = V_{rev} + V_{act} + V_{ohm} + V_{con}$	12
$\Delta G = zFV_{rev}$	13
$V_{rev} = \frac{\Delta G}{zF}$	14
$V_{act} = s \log\left(\frac{1 \cdot \frac{t_2}{T} \cdot \frac{t^3}{T^2}}{A} \cdot I + 1\right)$	15
$V_{ohm} = \frac{r_1 + r_2 \cdot T}{A} \cdot I$	16
$n = \frac{I \times t}{F \times z}$	17
$V_{H2(g)} = V_{O2(g)} = \frac{nRT}{P}$	18
$P_{total} = V \times I$	19
$V = I \times R$	20
$P_{ohmic} = I^2 \times R_{ohmic}$	21
$P_{electrolysis} = P_{total} - P_{ohmic}$	22
$Electrolysis \text{ Efficiency } (\eta) = \frac{P_{electrolysis}}{P_{total}} \times 100\%$	23

7.1. Model Representation with Simulink/Matlab

Figure 2 represents the mathematical model of PV array including fundamental components of diode, current source, series resistor and parallel resistor is modeled with Tags in Simulink environment. The simulation of solar module is based on equations given in the section above. After modeling each component separately, we can combine them to simulate the solar panel. And the PV's final model, as illustrated below [27].

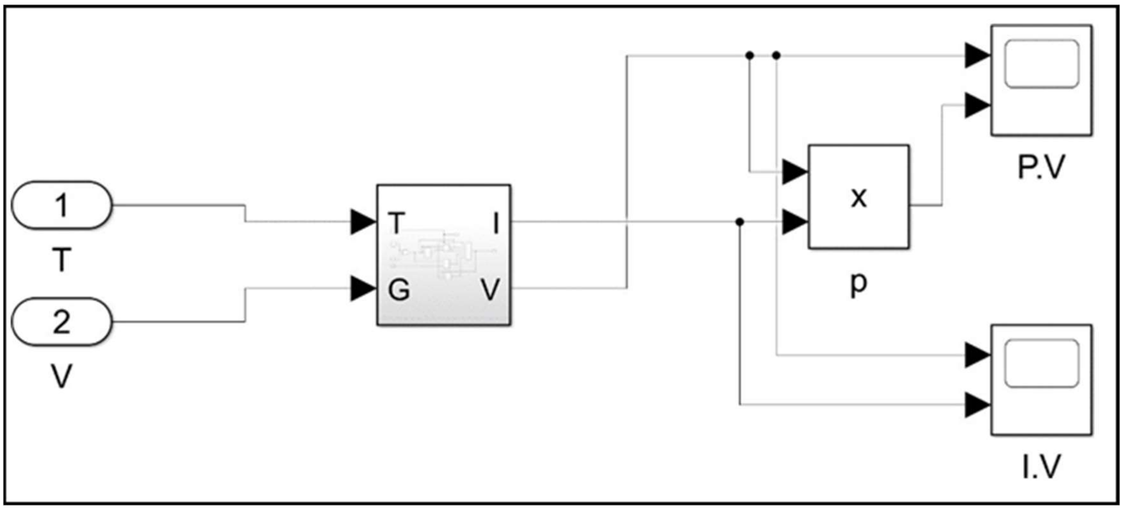

Figure 2. Photovoltaic arrays model using Simulink.

Figure 3 represents the solar photovoltaic P&O MPPT controller model developed in MATLAB/Simulink environment. And MPPT charge controller block. Inside the MPPT charge controller block consists of a Perturb & Observe MPPT algorithm. The MPPT charge controller block includes a P&O MPPT tracker and a lead-acid battery three-stage charger. The MPPT charge controller block outputs a PWM control signal to switch the switching device of the DC-DC converter. This is a common design for many commercial solar PV MPPT battery charge controllers [28].

Figure 3 indicates that the PV array has been interfaced with the boost converter using a controlled voltage source. The inductor current which is same as the load current of the PV system is used as feedback for designing the PV array. The output of the filter which is the control signal is compared with the saw-tooth waveform to generate the PWM signal which is fed as gate signal to the switches output current of the PV array and the converter inductor current are the same, so the MPPT algorithm can observe the array output power and optionally use the converter inductor current as the control variable. A comparison between actual and reference values for PV terminal voltage and maximum power available from PV array will control the duty ratio of boost converter.

Figure 4: Overviews the battery model developed in MATLAB/Simulink environment. The Battery block implements a generic dynamic model that represents the most popular types of rechargeable batteries [29]. To represent the temperature effects of any battery type, an additional discharge curve at ambient temperature, which is different from the nominal temperature, and the thermal response parameters are required. Additional discharge curves are not usually provided on the data sheet and may require simple experiments to be obtained.

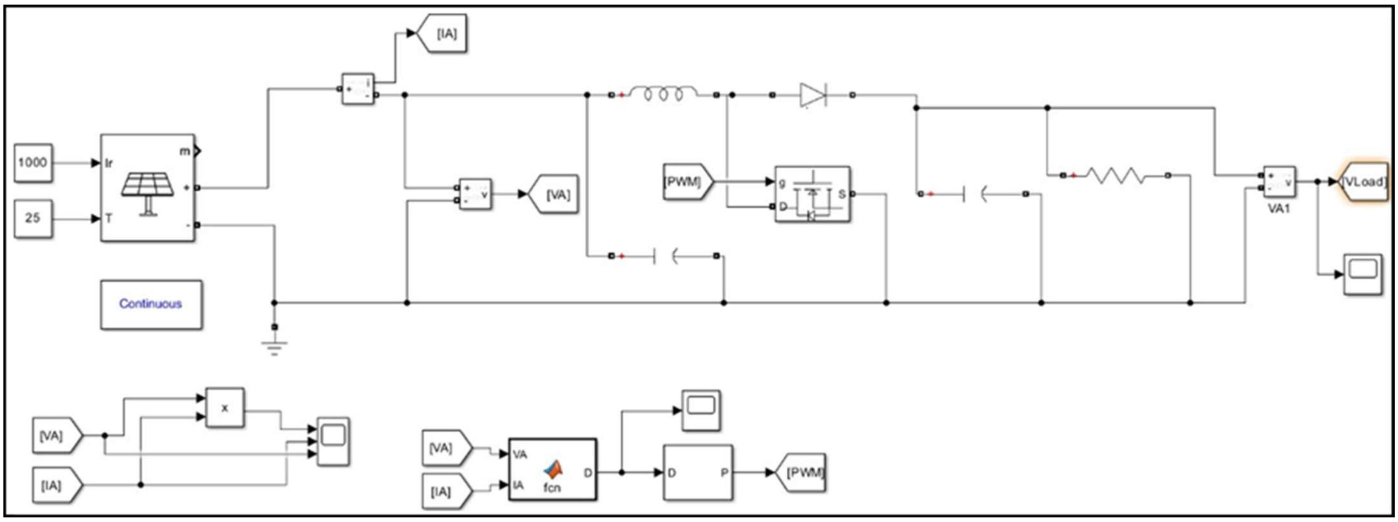

Figure 3. Perturb and Observe (P&O) MPPT Simulink model.

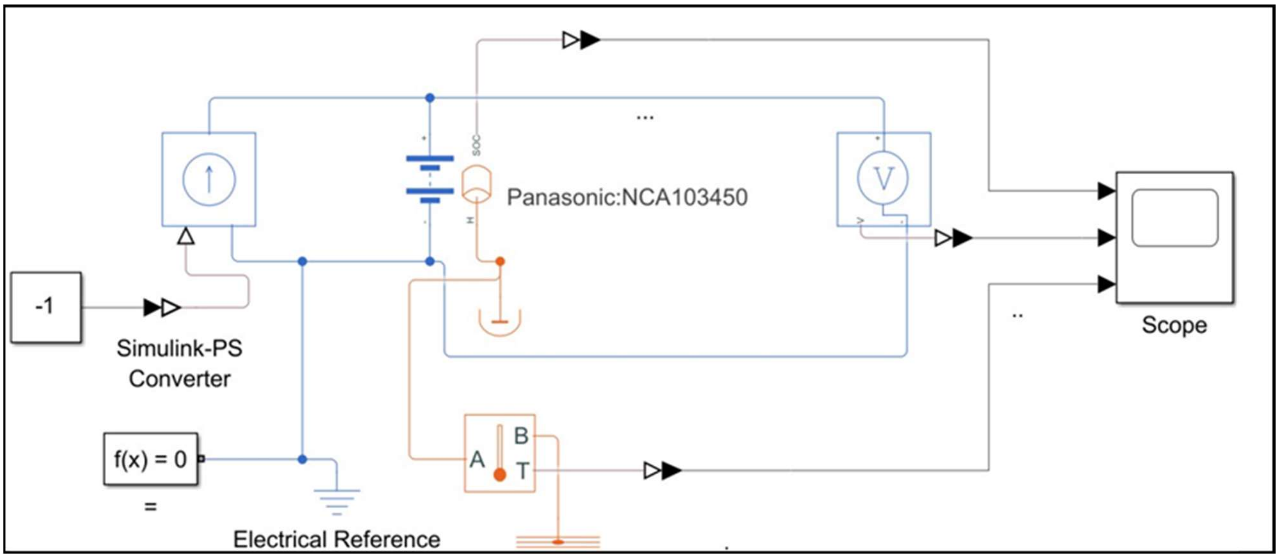

Figure 4. Simple Battery model using Simulink.

Table 3 defines the parameter applied in the mathematical model.

Table 3. The parameters used in the mathematical model, providing their definitions, values, and units.

Variable	Definition	Value/Unit
I_{ph}	Photo current	Output/Input
I_{sc}	Short circuit current	8.21 A
K_i	Shot circuit current at STC	0.0032 A
T	Operating Temperature	Input (User)
T_n	Nominal Temperature	298 K
G	Solar Irradiance	Input (User)
q	Electron charge	1.6 e^{-19}
V_{oc}	O.C Voltage	Panel
n	Ideality factor of diode	1.3
k	Boltzmann constant	1.38 e^{-23}
$Eg0$	Band Gap Energy of semi- conductor	1.1
Ns	Number of cells in series	54
Rs	Series resistance	0.221
Rsh	Shunt Resistance	415.405
Vt	Diode Thermal Voltage	-
T	Time	Hour
Ah	Ampere Hour rating of battery	Ah
A	Current	A
Q	Battery capacity	Wh
V_{rev}	Reversible Voltage	1.229 V
A	Area of Electrode	0.25 Cm^{-2}
F	Faraday's Constant	96485 $Cmol^{-1}$
z	Number of Electrons	2
S	Coefficient for overvoltage on electrodes,	0.185 V
t_1	Coefficient for overvoltage on electrodes	1.002 A^{-1} m^2
t_2		8.424 $A^{-1}m^2$ °C
t_3		247.3 $A^{-1}m^2$ °C
r_1	Parameter related to ohmic resistance of electrolyte	8.05e^{-5} Ωm^2
r_2		−2.5e^{-7} Ωm^2
I	cell current	4 A
t	time	30 s
R	universal gas constant	0.082 L atm K^{-1} $Cmol^{-1}$
P	Operating pressure	1 atm
T	operating temperature	27 °C

The 100 W solar power module is used as a template module for simulation of a solar panel and comprehensive module parameters.

Table 4. Electrical characteristics data of DS-100 M PV module.

Name	Ds-100M
Rated Power (Vmp)	100 W
Voltage at maximum power (Vmp)	18 V
Current at maximum power (Imp)	5.55 A
Open circuit voltage (Voc)	21.6 V
Short circuit current (ISC)	6.11 A
Total number of cells in series (NS)	36
Total number of cells in parallel (NP)	1
Maximum system voltage	1000 V
Range of operation temperature	−40 °C to 80 °C

7.2 Solar Radiation and Weather of Tabuk

The figure below shows the projected solar radiation at Tabuk for the day of 26 May 2023, from 6 am to 7 pm. [30]. Figure 5 shows the amount of solar irradiance, in W/m^2, incident on a horizontal surface in the Tabuk region of Saudi Arabia between 6:00 and 7:00 PM. The quantity of solar irradiance is quite low, ranging from 16 to 945 W/m^2. The irradiance, on the other hand, follows a diurnal pattern, reaching its zenith at 945 W/m^2 around 1:00 PM, and subsequently declining in both the morning and afternoon. The data demonstrates that the sun irradiation in the Saudi Arabian province of Tabuk fluctuates greatly between and throughout the day. The solar radiation in Tabuk is relatively high, with an average of around 5.5 kWh/m^2 per day. This means that there is a lot of potential for solar energy production in the region. Planning solar energy initiatives and maximizing the efficiency of solar panel design can both benefit from the knowledge presented here.

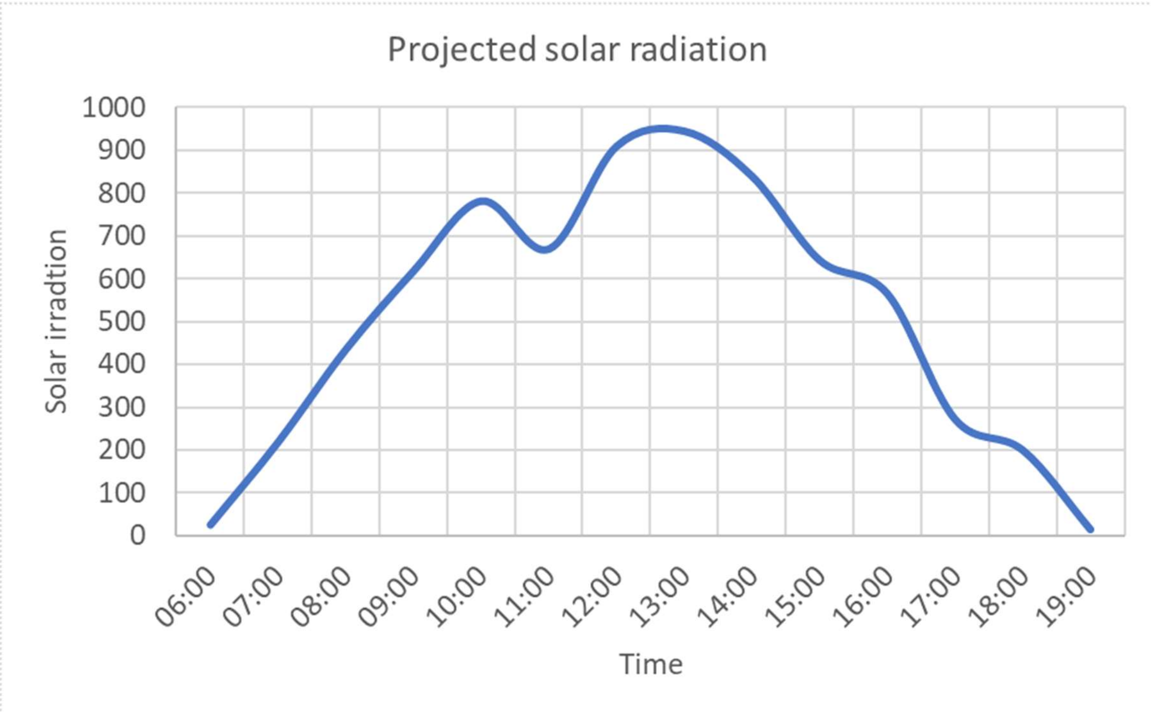

Figure 5. The projected solar radiation at Tabuk for the day of 26 May 2023.

8. Results

Understanding the availability of solar energy in the area requires knowledge of the total daily incident sun irradiance on the horizontal surface for the Tabuk region in KSA. This data can be used to evaluate the viability of harnessing solar energy for a variety of purposes, such as producing green hydrogen through electrolysis. However, it is also crucial to consider how solar radiation varies throughout the year and to incorporate these variations into the system's design. Using energy storage devices or taking other precautions to ensure that the Electrolysis system can function even during times of low solar radiation may be necessary due to the decreased solar radiation in the winter and fall.

Figure 6 shows the PV panel output voltage, current, and power curves at different solar intensities. The curves show that the output voltage of the PV panel increases with increasing solar intensity, while the output current decreases. This is because the PV panel is able to generate more power at higher solar intensities. Table 5 summarizes the numeric data for PV performance at different solar intensities The maximum power point (MPP) of the PV panel is the point on the curve where the power output is the highest. The MPP voltage and current are the values of voltage and current at the MPP. The fill factor (FF) of the PV panel is a measure of how efficiently the panel converts sunlight into electricity. The FF is calculated as the ratio of the area of the MPP to the area of the entire I-V curve. The higher the FF, the more efficient the panel is. The efficiency of the PV panel is the ratio of the output power of the panel to the input power of the sunlight. The efficiency is calculated as the area under the MPP curve divided by the area under the entire I-V curve. Greater efficiency denotes superior panel performance. The I-V and P-V characteristics illustrate that as irradiation levels rise, both current and voltage outputs increase proportionally. This results in a rise in power output in this operating condition.

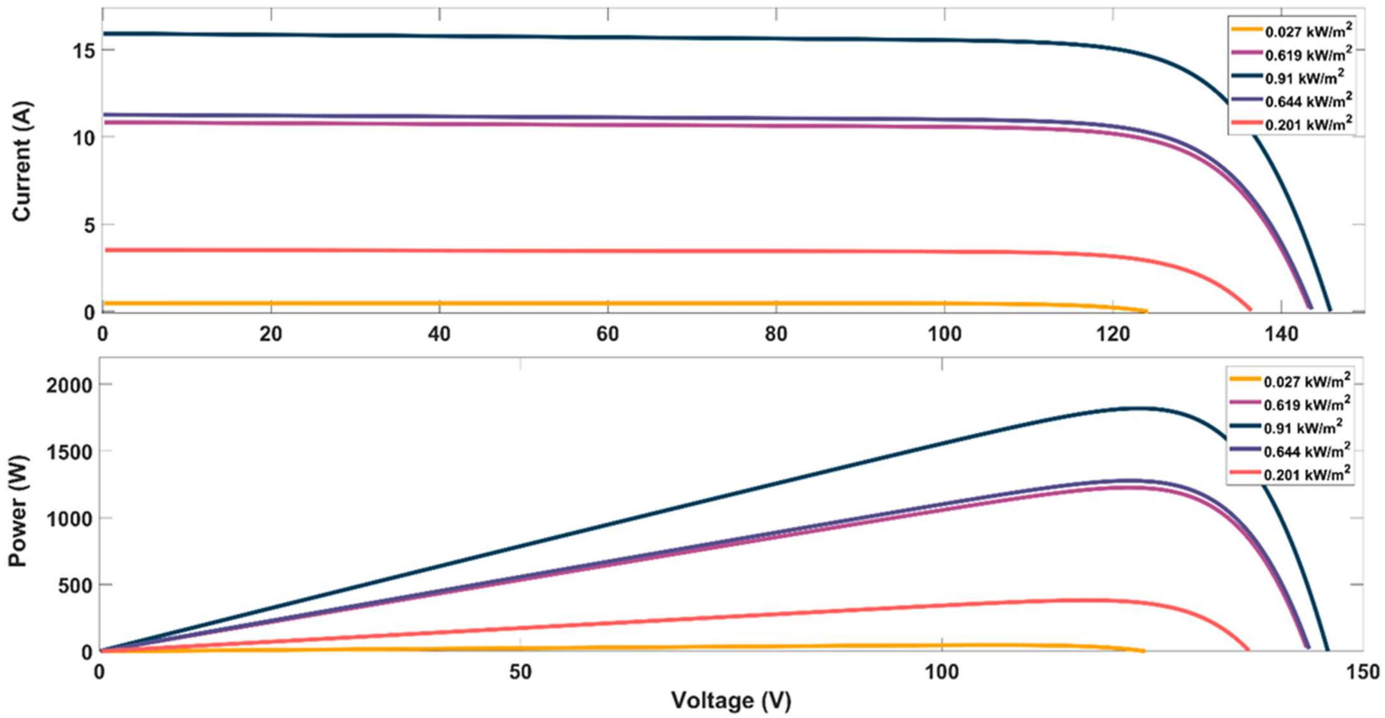

Figure 6. P-V and I-V characteristics.

The output current of the PV array and the converter inductor current are the same, so the MPPT algorithm can observe the array output power and optionally use the converter inductor current as the control variable. A comparison between actual and reference values for PV terminal voltage and maximum power available from PV array will control the duty ratio of boost converter.

Table 5. The numeric data for PV performance at the different solar intensities

Solar Intensity, W/M²	VOC, V	ISC, A	MPP Voltage, V	MPP Current, A	MPP Power, W	FF, %	Efficiency, %
1000	58.5	5.5	42.5	4.5	191	77	19.10
800	56.5	5.2	41.0	4.3	180	75	18.00
600	54.5	4.9	39.5	4.1	169	73	16.90
400	52.5	4.6	38.0	3.9	158	71	15.80

Figure 7 shows the characteristics of a Perturb and Observe (P&O) MPPT simulation. The P&O method is a simple and effective way to track the maximum power point (MPP) of a photovoltaic (PV) module. The simulation shows the power and current curve of the system, as well as the voltage curve. The power curve shows that the power output of the system increases as the voltage increases, until it reaches the MPP. The current curve shows that the current output of the system decreases as the voltage increases, until it reaches the MPP. The voltage curve shows that the voltage output of the system increases smoothly as the power output increases. The simulation shows that the P&O method is able to track the MPP of the system accurately. The power output of the system is always at the MPP, and the current and voltage outputs are always consistent with the MPP. The simulation also shows that the P&O method is relatively slow to track the MPP. The power output of the system takes a few milliseconds to reach the MPP after a change in the voltage. This is because the P&O method works by perturbing the voltage and then observing the change in the power output. The system takes a few milliseconds to complete this process. Overall, the simulation shows that the P&O method is a simple and effective way to track the MPP of a PV module. The method is accurate, but it is relatively slow.

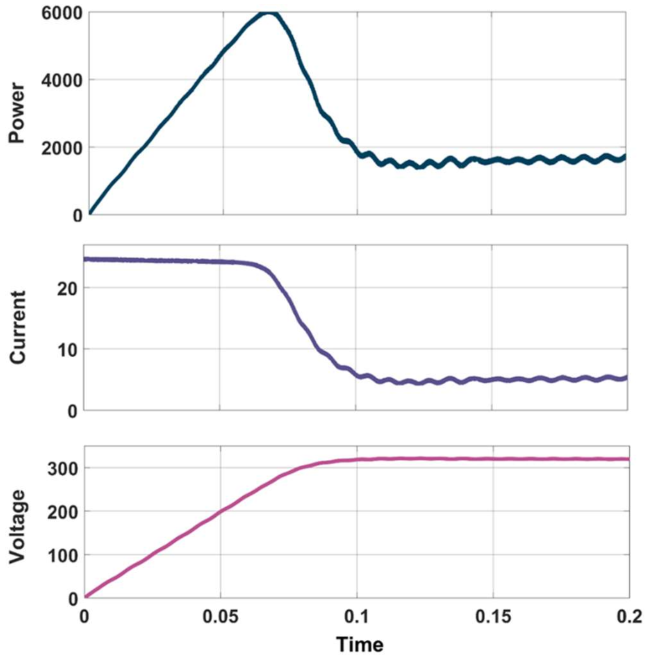

Figure 7. Characteristic of P&O MPPT simulation.

Figure 8 shows the characteristics of a 12 V 100Ah lithium battery in terms of temperature, voltage, and state of charge (SOC). The curves show that the voltage of the battery decreases as the temperature decreases, and the SOC of the battery decreases as the temperature increases. The data from the curves shows that the voltage of the battery is 3.9 volts at 298 K (25 °C), and it decreases to 3.6 volts at 290 K (23 °C). The SOC of the battery is 100% at 298 K (25 °C), and it decreases to 80% at 290 K (23 °C). The relationship between temperature and voltage is due to the fact that the electrolyte in the battery becomes less conductive as the temperature decreases. This results in a decrease in the current that can flow through the battery, which in turn results in a decrease in the voltage. The relationship between temperature and SOC is due to the fact that the chemical reactions in the battery are slower as the temperature decreases. This results in a slower discharge rate, which in turn results in a higher SOC. The curves in the image show that the lithium battery has a good temperature range. The battery can operate at temperatures up to 308 K (35 °C) without any significant degradation. However, the battery should not be operated at temperatures below 290 K (23 °C), as this can lead to a decrease in the capacity of the battery. Overall, the image shows that the lithium battery has good temperature characteristics. The battery can operate at a wide range of temperatures, and the voltage and SOC of the battery are relatively stable at different temperatures.

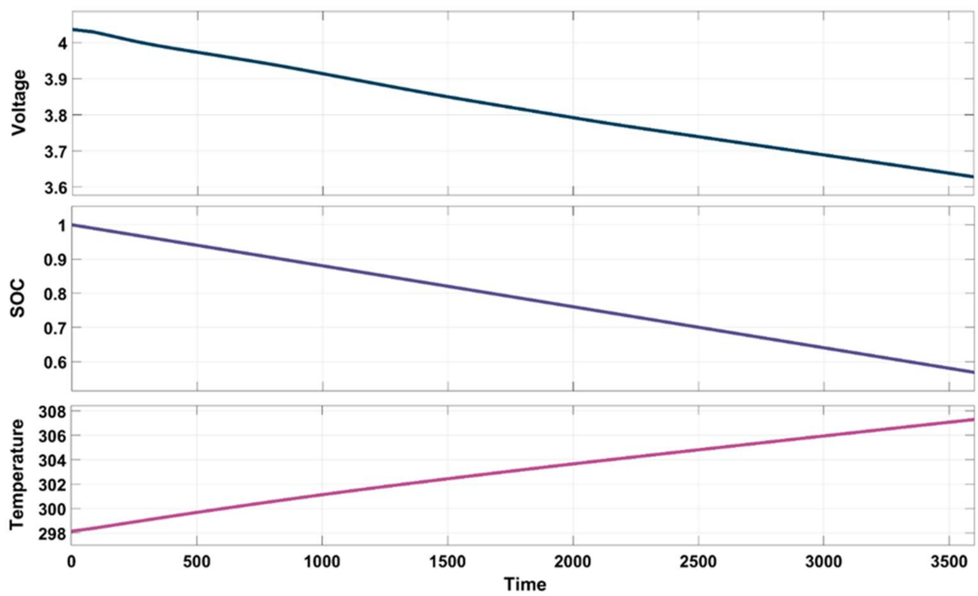

Figure 8. The lithium battery characteristics of temperature, voltage and SOC.

The numerical results of the seawater electrolyzer for hydrogen production show that:

The rate of hydrogen production is 4.8×10^{-4} moles per minute, which is equivalent to 12.0048 cubic centimeters per minute. This is a reasonable rate of hydrogen production, and it is comparable to the rates of other types of electrolyzers.

The efficiency of the electrolysis process is 55.86%. This means that 55.86% of the power input to the electrolyzer is used to produce hydrogen gas, and the remaining 44.14% is lost to ohmic resistance. The efficiency of the process could be improved by reducing the ohmic losses.

The ohmic losses are 5.29 watts. This is a significant amount of power, and it could be reduced by using a more efficient electrolyzer design or by using a higher-purity electrolyte.

The total power input to the electrolyzer is 12 watts. This is a relatively low power input, and it means that the electrolyzer could be powered by renewable energy sources, such as solar or wind power.

Overall, the results of the seawater electrolyzer are promising. The electrolyzer is able to produce hydrogen gas at a reasonable rate, and the efficiency of the process is relatively high. There is still room for improvement, but the electrolyzer has the potential to be a valuable tool for producing hydrogen gas from seawater.

9. Discussion

The study presents important results that shed light on the challenges and opportunities associated with green hydrogen production in the KSA. The research methodology used in the study focuses on the development and evaluation of a green hydrogen production system using solar energy and seawater electrolysis. The process involves various stages, including conceptual framework development, mathematical modeling, data collection and analysis, evaluation of green hydrogen production, and recommendations for future improvements. The study analyzes the solar radiation availability in the Tabuk region of Saudi Arabia, providing insight into the potential for harnessing solar energy. The data indicates variations in solar irradiance throughout the day and different seasons, making it essential to consider energy storage or backup systems during periods of low solar radiation. The article illustrates the PV panel's output characteristics at different solar intensities, showing how output voltage increases while current decreases with rising solar intensity. The Perturb and Observe (P&O) MPPT simulation demonstrates its effectiveness in accurately tracking the maximum power point of a PV module. The behavior of a 12 V 100Ah lithium battery in relation to temperature, voltage, and state of charge (SOC) is examined. The data highlights the battery's stable operation within a specific temperature range and the significance of maintaining optimal operating conditions. The numerical results of the seawater electrolyzer for hydrogen production are presented, indicating a reasonable rate of hydrogen production and an efficiency of 55.86%. The article also identifies potential areas for improvement, such as reducing ohmic losses and utilizing renewable energy sources for electrolyzer power.

The critical matter of system efficiency in renewable energy systems, specifically in relation to the dimensions of electrolyzers and batteries, as well as the challenge of electrolyzer instability during nominal power operation, will be explored in more detail below.

Electrolyzer and Battery Size: The size of the electrolyzer and battery in a renewable energy system is indeed a critical factor affecting efficiency and overall system performance. An appropriately sized electrolyzer and battery system ensures that energy generated from renewable sources, such as solar or wind, can be efficiently stored and used when needed. Undersized components can lead to energy wastage or system instability, while oversized components can increase upfront costs. In our study, we will provide more information on the sizing criteria and methodology employed to optimize these components for our specific setup in Tabuk, Saudi Arabia.

Electrolyzer Instability Under Nominal Power: Electrolyzer instability when operating under nominal power can significantly affect system reliability and efficiency. To address this issue, we will elaborate on the control strategies and mechanisms we employed to maintain stable operation, even under varying power conditions. This will include details on how we managed fluctuations in solar radiation and other external factors to ensure the consistent and reliable operation of the electrolyzer.

Continuous Operation and Device Lifetime: The ability of a system to work continuously is essential for achieving high efficiency and maximizing device lifetime. We will discuss the measures we implemented to enhance the continuous operation of our green hydrogen production system. This might include insights into system maintenance, fault detection, and recovery procedures that contribute to prolonged device lifetime.

Overall, the study provides valuable insights into the challenges and opportunities associated with advancing green hydrogen production in Saudi Arabia. The findings emphasize the importance of addressing technical limitations, improving efficiency, and exploring cost-effective solutions to unlock green hydrogen's potential as a sustainable and economically viable energy source in the country.

10. Conclusions

In conclusion, the research on advancing green hydrogen production in Saudi Arabia through harnessing solar energy and seawater electrolysis has provided valuable insights into the challenges and potential solutions for adopting this environmentally sustainable and economically viable energy solution.

The article highlights the critical obstacles that hinder the widespread adoption of green hydrogen in Saudi Arabia, including technical, economic, and social challenges. These challenges must be effectively addressed to fully unlock the potential of green hydrogen in the country and expedite the energy transition.

Through a comprehensive research methodology involving theoretical modeling and simulations using MATLAB and Simulink, the study presents a conceptual framework for a green hydrogen production system. This system incorporates solar panels, an advanced MPPT charge controller, an electrolyzer, a battery, and a seawater tank. Mathematical modeling and data analysis provide crucial insights into the system's performance and energy efficiency under different scenarios, considering variations in solar irradiance, system load, and electrolyzer capacity.

The results of the study demonstrate that the proposed system has promising capabilities, with the seawater electrolyzer exhibiting a reasonable rate of hydrogen production and a relatively high efficiency. However, challenges such as energy losses during electrolysis and the relatively high cost of green hydrogen production still need to be addressed to make the technology economically competitive.

The research paper presents the results of the proposed green hydrogen production system using solar energy and seawater electrolysis.

- The system demonstrates a reasonable rate of hydrogen production, equivalent to 12.0048 cubic centimeters per minute, with an efficiency of 55.86% in the electrolysis process.
- The study also highlights the need to consider seasonal variations in solar irradiance when designing green hydrogen production facilities. Theoretical experiments are conducted to evaluate the behavior of a lithium battery, which stabilizes the system's output during periods of low solar radiation.
- The simulation shows that the Perturb and Observe (PO) method is a simple and effective way to track the maximum power point (MPP) of a photovoltaic (PV) module. The PO method accurately tracks the MPP, but it is relatively slow in response time.
- The research emphasizes the importance of reducing ohmic losses in the electrolysis process, which currently accounts for 44.14% of power input. Suggestions for improving efficiency include using a more efficient electrolyzer design or a higher-purity electrolyte.

The research provides recommendations for enhancing the system's efficiency, reducing costs, and addressing technical challenges. Furthermore, the integration of renewable energy technologies and potential policy support can play a crucial role in scaling up green hydrogen production in Saudi Arabia.

Overall, this research represents a significant step towards advancing green hydrogen production in Saudi Arabia. By addressing the identified challenges and implementing the recommended solutions, the country can potentially benefit from a clean and sustainable energy source, contributing to a greener and more sustainable future.

Author Contributions

Conceptualization, H.S.A.; Methodology, H.S.A., H.F.A. and Z.F.S.; Validation, H.S.A., H.F.A. and A.A.A.; Formal Analysis, H.S.A.; Investigation, H.S.A., H.F.A., A.A.A and A.M.A.; Resources, H.S.A.; Data Curation, H.S.A. and H.F.A.; Writing Original Draft Preparation, H.S.A. and H.F.A.; Writing—Review & Editing, H.S.A.; Visualization, H.S.A., and H.F.A.

Ethics Statement

Not applicable.

Informed Consent Statement

Not applicable.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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