Advancements in Green Hydrogen Production using Seawater Electrolysis in Tabuk, Saudi Arabia

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Abstract

The transition to green hydrogen holds immense potential for addressing the pressing challenges of climate change, energy security, and sustainable development. Firstly, green hydrogen production relies on renewable sources such as wind, solar, and hydroelectric power, ensuring a significant reduction in greenhouse gas emissions compared to traditional fossil fuel-based hydrogen production methods. By embracing green hydrogen, nations can effectively mitigate climate change and achieve their emissions reduction targets outlined in the Paris AgreementThe production of green hydrogen, while promising in terms of its environmental benefits, faces a significant hurdle in the form of high production costs.This paper aims to explore the potential cost reduction in hydrogen production by designing an efficient electrolyzer that utilizes seawater as a feedstock. The use of seawater offers numerous advantages, including its abundance and easy accessibility, which can significantly lower production costs.Using MATHLAB, the mathematical models were solved in order to better understand the equipment and determine a system that is efficient. Overall, the work provides illuminating information about the use of green hydrogen systems and highlights the critical role that theoretical and experimental research plays in lowering the cost of such systems.

Keywords: Solar Energy, PV, Green Hydrogen, Seawater Electrolysis.

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1. INTRODUCTION

In 2022, for Saudi Arabia, the total electrical energy production increased by 0.77% in 2020 with 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 2019 when consumption was 288,713 GWh(General Authority for Statistics; http://www.stats.gov.sa/, 2020). The world's reliance on fossil fuels presents a few challenges, including environmental damage, securing supply and resources, and lack of sustainability.

Although conventionally sourced energy may have a lower initial cost than non-traditional energy sources like solar or geothermal, they are not as sustainable. Finding and using these fresh deposits is likewise getting more and more challenging. According to the International Energy Agency's (IEA) most recent projections, which were released at the end of 2019, the world's energy consumption would rise by 25% to 30% by 2040, which would result in an increase in carbon dioxide in an economy that depends on coal and oil. We aspire to build a future powered by clean energy sources like green hydrogen that is more accessible, efficient, and sustainable(Reichle, 2023).

And hydrogen can be created from water. In a procedure known as water electrolysis, the H2 and O are split apart. The method for creating hydrogen is called electrolysis, which entails "breaking" the water molecules with an electric current in an electrolyzer to release the dihydrogen (H2), (Henglein, 1969).

The chemical industry uses hydrogen as a raw material to create ammonia and fertilizers, the petrochemical sector uses hydrogen to refine petroleum, and the metallurgical industry uses hydrogen to create steel. These three sectors use hydrogen extensively, which results in significant carbon dioxide emissions. As a first step toward the urgent decarbonization of these sectors, we may employ green hydrogen as a raw material and create emissions-free steel. Due to its vast volume and extended lifespan, green hydrogen may be used as an energy storage system in a manner like how we currently employ strategic reserves of natural gas or oil. By doing this, we could provide the electrical system with renewable hydrogen reserves. Temperatures that are challenging to obtain with conventional environmentally friendly techniques can be reached with green hydrogen. As a result, one of the most potential uses for green hydrogen is in the production of energy and residential heating (Zakaria et al., 2023).

One of the keys to aiding in the decarbonization of transportation, particularly long-haul and air transportation, will be the use of green hydrogen as a fuel.Green hydrogen provides a clear substitute for extremely polluting fuels that are often utilized in marine transportation for long-distance ships. Green hydrogen can serve as the foundation for synthetic fuels in aviation that drastically cut emissions from this industry. Also, it will be necessary for the transportation of big products by road and rail.

Fuel-cell cars are powered by green hydrogen. Although this usage of green hydrogen is one of the ones that is most frequently mentioned, green hydrogen fuel-cell cars have not yet had a substantial impact on the automobile industry. (*IEA.Org*, n.d.).

2. LITERATURE REVIEW

The difficulties of deploying green hydrogen, and reducing its price and advancing this technology, according to numerous studies That in order to solve these problems,Conventional energy sources must be replaced with renewable energy sources.(Moritz et al., 2023).Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities.(Hai et al., 2023). Optimal design and transient simulation next to environmental consideration of net-zero energy buildings with green hydrogen production and energy storage system.(Haug et al., 2017). Process modelling of an alkaline water electrolyzer. (Abomazid, 2021). Modeling and Control of Electrolysis Based Hydrogen Production System.

2.1 History and Background

Hydrogen was initially discovered in 1766, and balloons were first flown with hydrogen gas in 1783. Then, in 1972, the first hydrogen-powered cars were introduced, but their use was limited due to the availability of alternative, more affordable energy sources. Hydrogen is regarded as an energy carrier or secondary energy source, like electricity, that can store and transport energy, as opposed to a primary energy source like petroleum, because it occurs in nature as combined molecules and requires energy input to obtain pure hydrogen, unlike petroleum, coal, and natural gas. When hydrogen is released into the atmosphere, it reacts with oxygen to form water, which is why hydrogen energy is frequently regarded as clean energy. However, it cannot be regarded as entirely clean if fossil fuels like coal and petroleum are employed in its manufacture. Only when it is created utilizing renewable energy sources like solar, wind, or waterpower then it can be regarded as clean. In general, hydrogen is categorized as grey hydrogen if it creates carbon dioxide (CO2), blue hydrogen if it catches and stores carbon dioxide, if it uses water electrolyzed hydrogen is categorized as green hydrogen.

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. 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.(*NEOM Accelerates Progress Towards Green Hydrogen Future*, n.d.).

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 CO2 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 discussed in the following sections of this paper.

(Badea et al., n.d.)Gives a perspective procedure for an environmentally clean commercial production of hydrogen by seawater as an „in situ" utilization of marine wave generated power is the seawater electrolysis.

(Yoong et al., 2012)The paper presents the feasibility study of solar hydrogen harvesting system using seawater instead of clean water to produce hydrogen. Besides, the system is proposed to operate offshore to avoid deforestation. In this system, solar irradiance collected by the Photovoltaic (PV) panel is first used to pump the seawater into the distillation tank. The distillation process of seawater takes place with direct sunlight via evaporation. Clean water obtained will be directed into electrolysis chamber and processed into hydrogen, which will be stored in metal hydride canister. The system model, overall process flow chart and total system efficiency have been studied and described.

(Cui et al., 2022)the paper summarizes the recent progress in advanced electrode materials with an emphasis on their selectivity and anti-corrosivity. Practical materials with improved selectivity for oxygen generation, such as mixed metal oxides, Ni/Fe/Co-based composites, and manganese oxide (MnOx)-coated heterostructures, are reviewed in detail.

2.3 Problem Statement

Green hydrogen still faces social, economic, and technical obstacles despite its potential to speed up the energy transition. Before green hydrogen can be produced and used in Saudi Arabia, these problems must be solved. When green hydrogen is electrolyzed, liquefied, or converted to other carriers, transported, and used in fuel cells, a significant amount of energy is lost. In order to use green hydrogen as a fuel, we need electrolyzers that can compete with end-use electrification. These losses, if not decreased, will require a significant use of naturally generated energy sources. It can be difficult to transport and store hydrogen, as it needs to be under intense pressure and liquefied at very low temperatures. Hydrogen can cause pipeline steel to become brittle and has the potential to leak more quickly than natural gas or propane. Another problem with hydrogen is that, in order to operate a fuel cell, it must be extremely pure, up to 99.999%. Green hydrogen production currently costs between 6-12 USD per kilogram, making it expensive.

3. METHODOLOGY

The paper discusses a system that uses sea water to produce green hydrogen that potentially can decrease cost. by looking at numerous designs and utilizing various mathematical simulations to discover the best system for the design. The mathematical model is solved using MATLAB, the data used in the mathematical modelswereobtained fromexperimentation and established parameters. This study employs a deductive methodology, beginning with the basis of theory.

4. SYSTEM DESCRIPTION

The Green hydrogen production system shown in Figure 1utilizes a solar-powered panel as a source of clean energy. The electrolyzer, a battery, an MPPT charge controller, a seawater tank, and a PV panel make up the system's five primary components of equipment.

The PV panels produce the power needed for producing hydrogen. The MPPT charger controller utilizes an algorithm to ensure that the electrolyzer receives the maximum amount of power and maintains a steady current to boost system efficiency. And the feedstock of electrolyte for the system comes from the sea water tank. We can ensure that the system runs for 24 hours by using the charge controller and battery simultaneously.

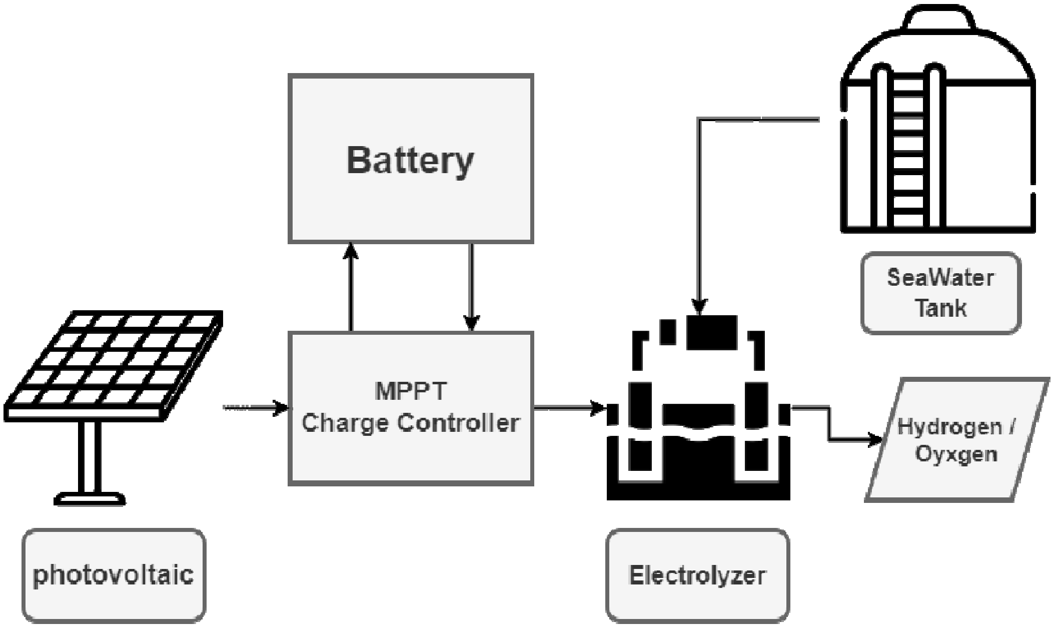

FIGURE 1: A schematic diagram of the proposed green hydrogen production system.

5. 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 hours and produce the greenest hydrogen for electrolysis. with the behavior of each component being described by mathematical equations. Check the mathematical representation below.

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
$I_{RS} = \frac{I_{SC}}{e^{\left(\frac{q \cdot V_{oc}}{n \cdot N_s \cdot K \cdot T}\right)} - 1}$	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
$\frac{\partial P}{\partial V} = 0 \text{ for } \mathrm{V} = \mathrm{V}_{mp}$	6
$\frac{\partial P}{\partial V} = 0 \text{ for } \mathrm{V} < \mathrm{V}_{mp}$	7
$\frac{\partial P}{\partial V} = 0 \text{ for } \mathrm{V} > \mathrm{V}_{mp}$	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

TABLE 1 : Equations.

5.1 Modeling various equations with the aid of MATLAB

FIGURE 2: Photovoltaic arrays model using Simulink.- A 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.(Pandiarajan & Muthu, 2011)

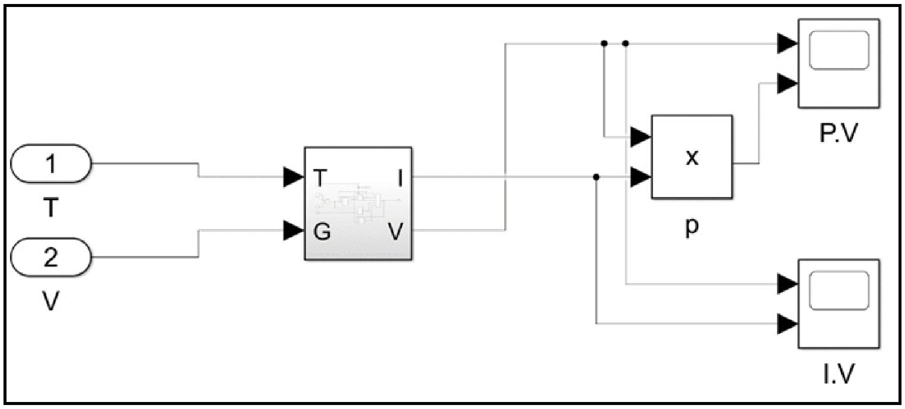

FIGURE 2: Photovoltaic arrays model using Simulink.

FIGURE 3: Perturb and Observe (P&O) MPPT Simulink model.- Overview of 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.(AHSAN MEHMOOD, 2021)

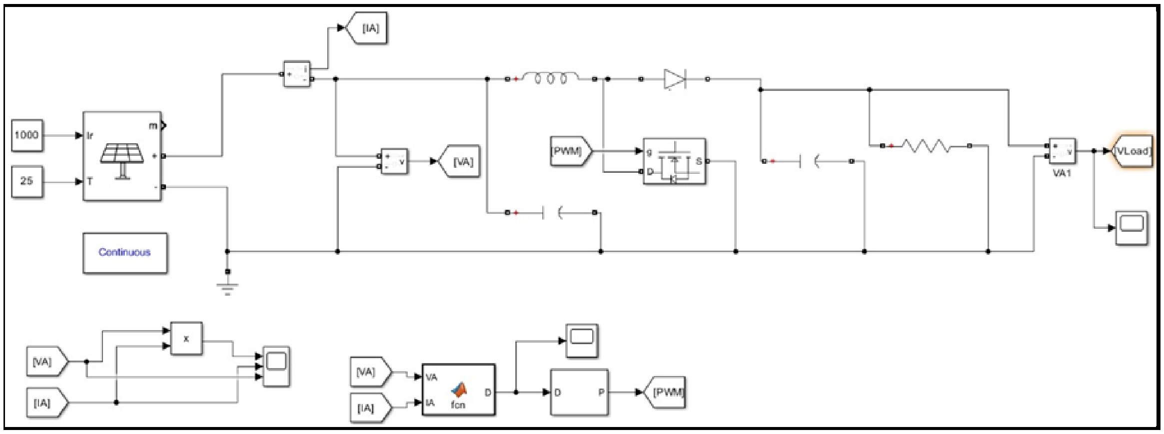

FIGURE 3: Perturb and Observe (P&O) MPPT Simulink model.

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: Overview of 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.(Gazzarri, 2022)

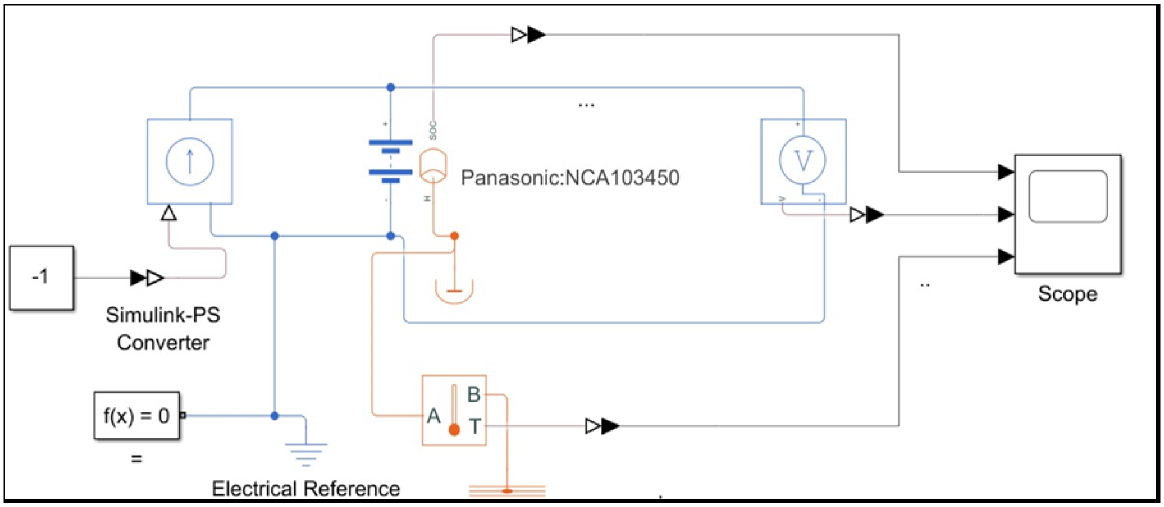

FIGURE 4: Simple Battery model using Simulink.

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.

The table below defines the parameter applied in the mathematical model.

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
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} ℃
t_3		247.3 A^{-1}m^{2} ℃
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 ℃

TABLE 2: The parameters used in the mathematical model, providing their definitions, values, and units.

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

Name	Ds-100M
RatedPower(Vmp)	100 W
Voltageatmaximum power(Vmp)	18V
Currentatmaximumpower(Imp)	5.55A
Open circuit voltage(Voc)	21.6V
Shortcircuitcurrent(ISC)	6.11A
Totalnumberofcellsinseries(NS)	36
Totalnumberof cellsin parallel (NP)	1
Maximumsystemvoltage	1000V
Rangeofoperationtemperature	-40℃to 80℃

TABLE 3 : Electrical characteristics data of DS-100 M PV module.

The Figure below shows the projected solar radiation at Tabuk for the day of May 26, 2023, from 6 am to 7 pm.(TuTiempo, n.d.)

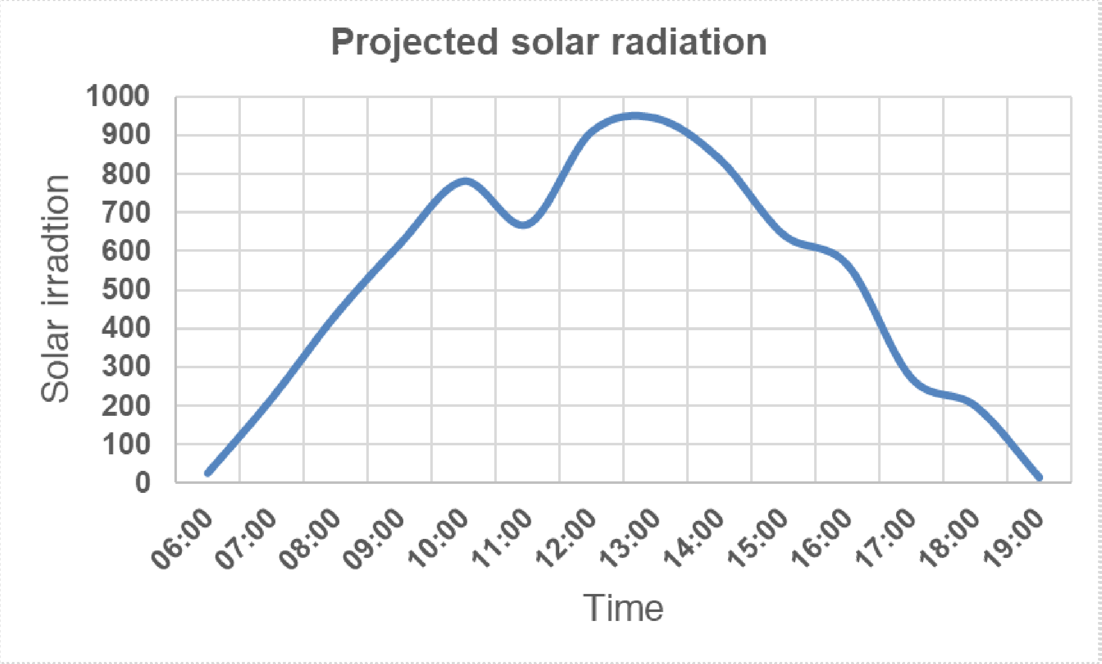

FIGURE 5: the projected solar radiation at Tabuk for the day of May 26, 2023.

6. RESULTS AND DISCUSSION

6.1 Solar radiation and weather of Tabuk

FIGURE 5: shows the amount of solar irradiance, in W/m2, 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/m2. The irradiance, however, rises during the day, peaking at 945 W/m2 at 1:00 PM, and then begins to fall once more. morning and afternoon, with an increase in the morning. The data demonstrates that the sun irradiation in the Saudi Arabian province of Tabuk fluctuates greatly between and throughout the day. Planning solar energy initiatives and maximizing the efficiency of solar panel design can both benefit from the knowledge presented here.

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.

6.1.1 I–V and P–V characteristics under Different irradiation with constant temperature are given below:

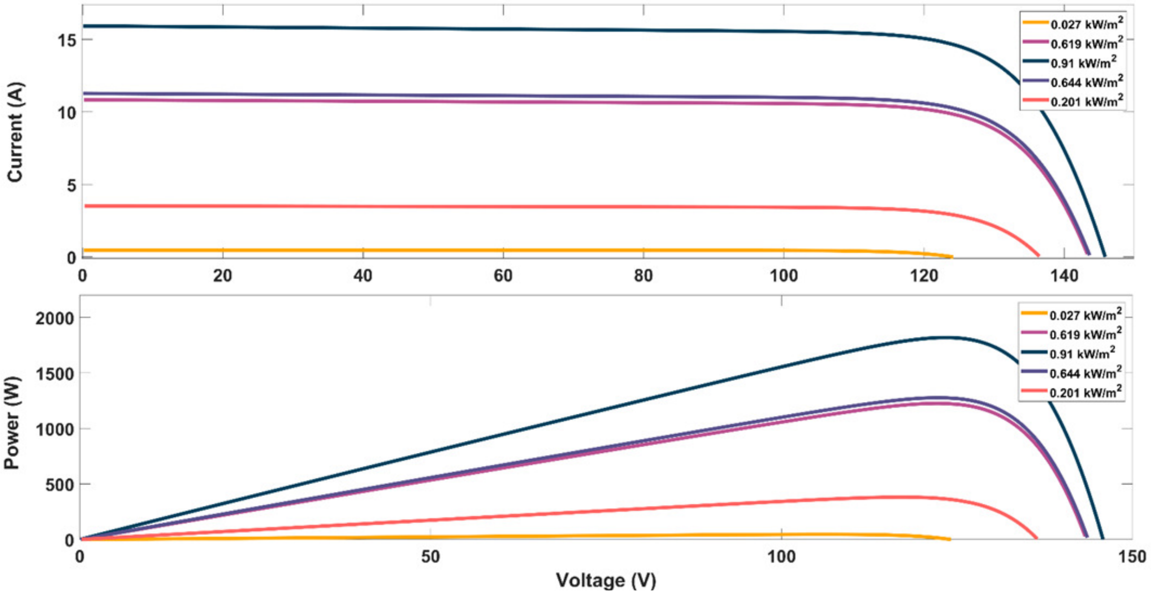

FIGURE 6: P-V and I-V characteristics.

I-V and P-V Characteristic Showcase *when* the irradiation increases, the current and voltage output increase. This results in a rise in power output in this operating condition.

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.

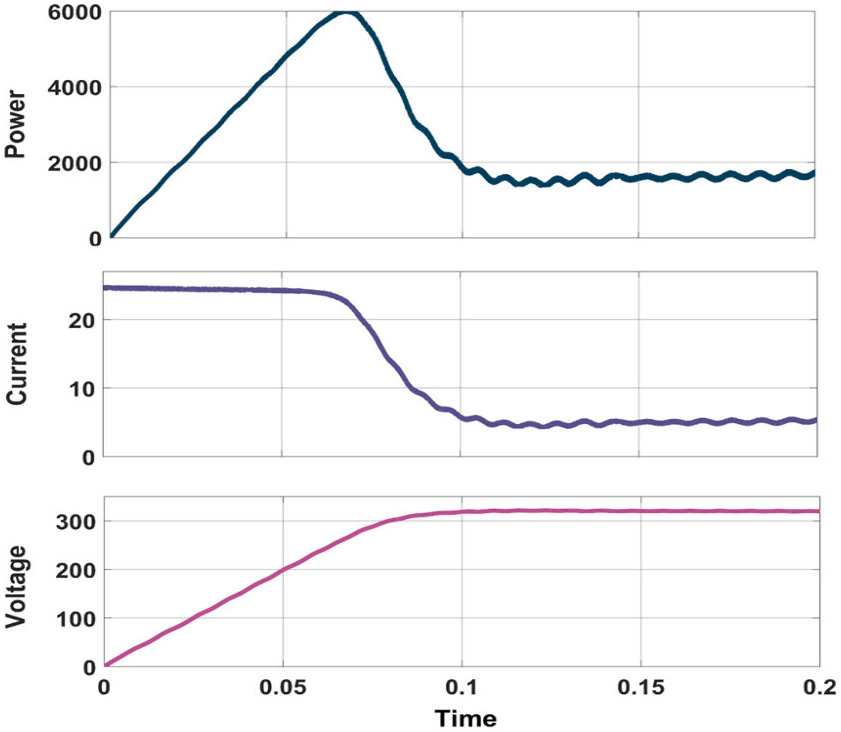

FIGURE 7: Characteristic of P&O MPPT simulation.

6.2 The Performance of Battery and Theoretical Experiment

We utilized a 12v 100Ah lithium battery model based on the equations from **TABLE 1** to simulate the battery's charge and discharge behavior. By applying a charge of 12A and a discharge of 10A, we calculated the battery's capacity, which amounted to 2400 Wh. The charging process will take approximately 8.3 hours to reach full capacity. For simulation purposes, we employed a MATLAB model representing a Panasonic NCA103450 Battery with 1 Amps by applying the data

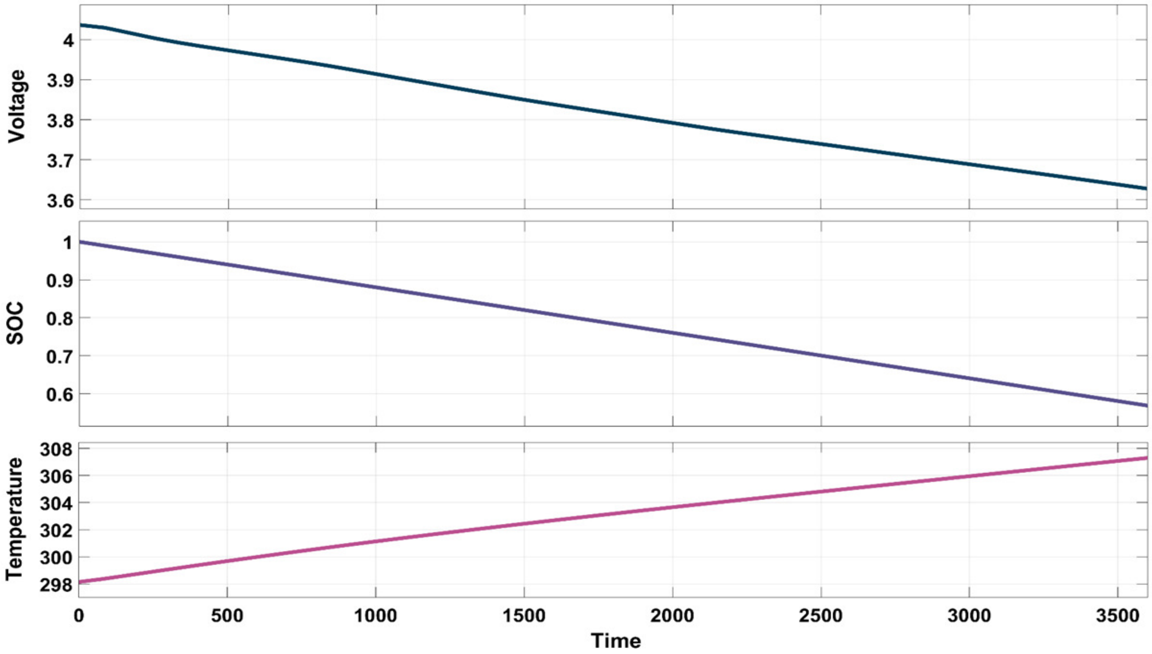

FIGURE 8: The characteristics of temperature and voltage and SOC.

from the preceding theoretical experiment to the electrolysis model equations. We can calculate the power and efficiency as well as the flow rates of hydrogen and oxygen gas.

symbol	Results	Units
$n_{H2(g)}$	4.881×10^{-4}	mol min^{-1}
$V_{H2(g)}$	12.0048	cm^3min^{-1}
$n_{O2(g)}$	2.44×10^{-4}	mol min^{-1}
$V_{O2(g)}$	6.0024	cm^3min^{-1}
P_{total}	12	w
R_{ohm}	0.331	Ω
P_{ohm}	5.296	w
$P_{electrolysis}$	6.704	w
Electrolysisefficiency(η)	55.86	%

TABLE 4: Theoretical experiment results(Sanath et al., 2017).

The study offers helpful insights on the use of electrolysis, that uses clean energy source that is appropriate for regions with high solar irradiance, to produce green hydrogen. The paper provides a mathematical model and equations to assess the possible effects of using sea water as the electrolysis system's feed stock. The report makes the case that using seawater as the system's feed stock would be a way to reduce the high cost of hydrogen production in Saudi Arabia. The study also highlights how crucial it is to consider how solar radiation varies throughout the year and design the system to account for these variations. Overall, the paper advances the development of green hydrogen production that is more effective and sustainable.

The research proposes the use of seawater electrolysis as a means to reduce the high production costs associated with green hydrogen production. This approach offers advantages such as the abundance and easy accessibility of seawater, which can significantly lower production costs. By designing an efficient electrolyzer system that utilizes seawater as a feedstock, the research aims to contribute to the development of more effective and sustainable green hydrogen production methods. The mathematical models and equations provided in the research help assess the effects of using seawater as the electrolysis system's feedstock. This provides valuable insights into the potential cost reduction and efficiency improvements that can be achieved through this approach.

The research highlights the critical role of theoretical and experimental research in lowering the cost of green hydrogen systems. By exploring the use of seawater electrolysis, the research opens up possibilities for advancements in green hydrogen production that can address the challenges of climate change, energy security, and sustainable development.

Overall, the proposed research introduces the potential for cost reduction, efficiency improvements, and environmental benefits in green hydrogen production through the utilization of seawater electrolysis.

7. CONCLUSION

The primary research question that our study aims to address is:"How can the utilization of seawater electrolysis in Tabuk, Saudi Arabia, contribute to the cost-effective production of green hydrogen, and what are the theoretical and practical implications of such a system?" This research question forms the foundation of our investigation into the feasibility and benefits of using seawater electrolysis for green hydrogen production in the specific context of Tabuk.

The data offered in the article offers crucial details on the temperature in Tabuk region of Saudi Arabia, and solar irradiance. The amount of solar irradiance fluctuates greatly during the day, with summer experiencing the highest levels. Additionally, Tabuk experiences large daily and seasonal temperature variations. The strong solar radiation throughout the summer can be used to the Electrolyzer's advantage, ensuring that they can produce green hydrogen that is both affordable and sustainable. Planning solar energy projects and maximizing the efficiency of solar panel design can both benefit from the data. The findings show that creating green hydrogen from sea water is more cost-effective because it is plentiful and sustainable.In order to ensure the best efficiency and lowest production costs, the data recommends that the electrolyzer should be designed and run with the summer season in mind, employing solar panels and MPPT controllers.

It should be highlighted that there may be a few factors influencing the price of creating green hydrogen, including the necessity for developing appropriate technologies and the absence of infrastructure for the transport and storage of hydrogen. The most effective techniques to maximize green hydrogen generation and the efficiency of the Electrolyzer may require further investigation and review of the data.

The research on green hydrogen production using seawater electrolysis has several practical implications:

- It offers a potential solution to the high production costs associated with green hydrogen production, by utilizing seawater as a feedstock, which is abundant and easily accessible .
- The use of seawater as a feedstock can significantly lower production costs, making green hydrogen more affordable and economically viable .
- The research highlights the importance of theoretical and experimental research in lowering the cost of green hydrogen systems, emphasizing the need for further advancements in technology and infrastructure for the transport and storage of hydrogen .
- The findings suggest that designing and running the electrolyzer system with the summer season in mind, utilizing solar panels and MPPT controllers, can maximize efficiency and further reduce production costs .
- The data provided in the research can be used to plan solar energy projects and optimize the design of solar panels, taking advantage of the strong solar radiation in the Tabuk region of Saudi Arabia .

8. CONFLICTS OF INTEREST

The authors declare that they have no known financial or interpersonal conflicts that would have appeared to have an impact on the research presented in this study.

9. DATA AVAILABILITY

On reasonable request, the corresponding author will provide the information supporting the study's conclusions.

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