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Potential of Hydrogen Production System from Wind Generation

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Abstract

This study combines wind energy with hydrogen generation to help achieve Sustainable Development Goal 7 (Affordable and Clean Energy). It aims to create an efficient, cost-effective, and sustainable hydrogen manufacturing mechanism based on wind energy. Key objectives include modelling hydrogen production, examining the link between hydrogen output and wind input, and assessing system efficacy. The study aims to create a hydrogen production model using wind power generation, analyse the model's output in terms of hydrogen levels and wind energy input, and validate the model's performance by calculating the hydrogen mass rate, volume rate, and system pressure. The model was tested using wind speeds ranging from 1.75 m/s to 12.0 m/s, representing real-world conditions from different geographical locations. Across this range, the system demonstrated a significant improvement in energy efficiency, with energy consumption dropping from 136.51 kWh/kg to 35.29 kWh/kg of hydrogen produced. Simultaneously, electrolyzer power output increased from 22.4 kW to 31.3 kW, validating the model's ability to capture the dynamic relationship between wind variability and hydrogen production performance. The scope comprises creating a complete model in MATLAB and optimising the efficiency of a hybrid wind-hydrogen generation plant. This project intends to make a substantial contribution to the transition to a sustainable, low-carbon energy future by addressing critical technological, economic, and environmental issues of wind-generated hydrogen.

Keywords

Hydrogen Production, Wind Energy, Simulation

1. Introduction

Modelling a hydrogen production system using wind energy is at the frontier of innovation, combining renewable energy with sustainable fuel technology. This initiative attempts to use wind energy to generate hydrogen by electrolysis, advocating green hydrogen as a viable alternative to fossil fuels. This programme is consistent with worldwide efforts towards decarbonisation and sustainable energy alternatives. The project aims to address problems in efficient and cost-effective hydrogen generation by utilising modern modelling approaches, as well as to investigate its integration as an energy carrier in a variety of applications. The environmental advantages are enormous, as harnessing wind power to produce hydrogen decreases dependency on fossil fuels and lowers greenhouse gas emissions. This is consistent with global climate change mitigation initiatives. Furthermore, the project focuses on energy storage methods, allowing for steady hydrogen gas generation without the need for extra storage devices, assuring a consistent hydrogen supply. The problem statement emphasizes the need for a comprehensive modelling framework for hydrogen generation from wind energy that prioritises efficiency, cost-effectiveness, and sustainability. This modelling approach distinguishes itself from previous work by integrating detailed electrical component behavior of rectifier and buck-boost converter with dynamic wind conditions and hydrogen production performance, enabling a more accurate, system-wide efficiency analysis. Unlike many prior studies that focus solely on wind resource assessment or electrolyzer performance in isolation, this framework provides a holistic, real-time simulation that captures interactions across the entire wind-to-hydrogen performance such as mass, pressure and power filling a critical gap in the literature regarding end-to-end optimization for variable renewable inputs. Hydrogen's adaptability and environmental benefits make it a viable alternative to fossil fuels, coinciding with SDG 7 (Affordable and Clean Energy).

2. Hydrogen

Concerns about fossil fuels' environmental effect drive the transition to sustainable, carbon-neutral fuels. Fossil fuels release enormous amounts of CO_2, increasing climate change. Transitioning to sustainable choices such as hydrogen, which is created by electrolysis using renewable energy, provides great energy density and adaptability. It drives fuel cells, which generate electricity with just water as a byproduct, and combustion engines, which produce only water and heat [1]. The International Energy Agency reports a significant increase in hydrogen consumption since 1975, with worldwide demand exceeding 70 million metric tons in 2019, primarily from fossil fuels [2]. Countries must diversify their investments to promote green alternatives in the absence of present legislation.

2.1. Wind Energy

Wind energy, which dates back over three thousand years, is seeing a rebirth due to its environmental and economic advantages [3]. Originally utilized for purposes like water pumping, it faced competition in the twentieth century but has since increased due to technical advancements and favorable legislation [4]. Improved turbine technology has increased yearly energy yields by 5% while lowering weight and noise [4]. Mathematical models such as the Weibull and Rayleigh distributions are critical for determining energy production potential and site selection [4]. Despite its expansion, wind energy has obstacles such as vibration and noise; yet technological improvements provide solutions such as supervisory controls and simulation models [4]. Global trends and regulations encourage wind energy expansion, doubling grid-connected capacity every three years, seeking to reduce fossil fuel dependence and battle climate change. US research investigates the use of wind energy for green hydrogen generation, citing large wind potential and present production gaps [5]. Green hydrogen, with four times the energy density of petrol or diesel, is considered a feasible energy source [6]. An example study implies that an 8-MW turbine in Texas might fulfil substantial hydrogen demand, emphasising the importance of precision turbine placement owing to regional wind variability [5].

2.2. Hydrogen Production

The transition to a hydrogen-based economy will first require the use of fossil fuels, particularly natural gas, which emits less carbon than oil and coal. Integrating hydrogen into existing natural gas infrastructure is both technically viable and economically beneficial [7]. Environmental advantages are dependent on manufacturing purity and technology. Hydrogen kinds are categorised by colour. Grey hydrogen is produced from hydrocarbons with CO_2 emissions [8]. Blue hydrogen is derived from hydrocarbons and uses carbon capture and storage (CCS) to regulate emissions. Green hydrogen is produced using water electrolysis utilising renewable energy, with low emissions [9]. Other hydrogen varieties include brown (from coal gasification), turquoise (from methane pyrolysis), and pink (from water electrolysis using nuclear power) [9]. There are more techniques for splitting water, such as thermochemical and photocatalytic [10]. Economic reasons, technological preparedness, and scalability are all significant difficulties for sustainable hydrogen generation technologies. Methane reforming is popular because to its viability, particularly for automotive applications, although blue hydrogen is valued for its cost advantage over electrolysis [10].

2.3. Electrolysis

Water electrolysis converts water into hydrogen and oxygen using electrical energy. The system consists of an anode, cathode, electrolyte (usually an aqueous solution or ceramic membrane), and power source. Electrolyser efficiency ranges from 65% to 75%, depending on electrode distance, electrolyte quantity, and operating temperature [11]. Compression, storage, and transmission of hydrogen result in losses of up to 35%, with an overall conversion efficiency of 70% for on-site consumption or injection into the gas network [12]. Fuel cell efficiency suffers from energy losses caused by electrical resistance and mass diffusion, resulting in a total process efficiency of 35% [13]. Commercial electrolysis uses two basic processes: alkaline and PEM (proton exchange membrane). Alkaline technique, which has been used for decades, is well-established yet inefficient. PEM technology is perfect for integrating renewable energy sources because of its high efficiency, low size, and operational adaptability [13].

2.4. Hydrogen Storage

Hydrogen, while being invisible and having no taste or odour, is becoming increasingly popular for energy delivery due to its high energy density and ubiquitous availability [14]. Effective hydrogen storage technologies are essential for developing sustainable energy sources. The several storage techniques are as follows:

- Compressed hydrogen gas storage is cost-effective but has a poor storage density [15].
- Liquid Hydrogen Storage: Provides great storage density but takes significant energy for cooling and is expensive [15].
- Hydride Storage: A solid metal absorbs hydrogen, resulting in high energy per unit volume but reduced energy per unit mass and sensitivity to material poisoning [15].
- Carbon-based materials are used for hydrogen physisorption because they have substantial surface areas and pore volumes that can store hydrogen [14].
- Chemical Hydrogen Storage: Involves chemisorbing hydrogen with compounds such as metal hydrides, which offers high-density storage but must solve material toxicity and storage capacity loss concerns [14].

Effective hydrogen storage technologies are critical to hydrogen's widespread use as a sustainable energy source. Each storage system has unique benefits and drawbacks, necessitating continual study and innovation to overcome limitations and improve efficacy.

2.5. Fuel Cell

Considering the global energy crisis and environmental concerns, hydrogen is emerging as an essential component of the transition to sustainable energy [16]. The European Commission, for example, is extensively financing hydrogen programmes with the objective of producing 50% of hydrogen from renewable sources by 2030 [16]. This increased investment highlights hydrogen's importance in tackling environmental issues and developing sustainable fuel solutions. Hydrogen fuel cells use electrochemical principles with hydrogen and oxygen to produce electricity, water, and heat as byproducts [17]. The fuel cell stack, like a battery, consists of an electrolyte membrane sandwiched between electrodes, which are supported by auxiliary components in the Balance of Plant (BoP), such as heat and water management systems [17]. Integrating hydrogen fuel cells into marine transportation offers significant environmental advantages, such as a projected 70% decrease in carbon emissions by 2030 and carbon neutrality by 2050 [18]. These fuel cells have great energy conversion efficiency and produce no pollutants, making them a sustainable energy source [17].

Despite these benefits, obstacles persist, demanding economic and environmental impact studies to maximise hydrogen fuel utilisation [16]. Overcoming these barriers is critical for the broad implementation of fuel cell hydrogen technology. Hydrogen fuel cell cars are a successful implementation of this technology, utilising both fuel cells and lithium batteries for energy management in transportation [19]. With worldwide momentum and major investments driving hydrogen sector growth, the future appears bright for fuel cell hydrogen technology.

3. Methodology

The procedure starts with initialising system parameters such wind energy input, wind turbine model, electrolyzer model, hydrogen storage system, and display settings. Wind energy input is processed by the wind turbine model to determine mechanical power output, which is subsequently transformed to electrical power. This electrical power powers the electrolyzer, which generates hydrogen gas. The hydrogen gas is kept in the hydrogen storage system. Simulation results are shown, and the procedure is repeated until the simulation is complete.

Figure 1 is a process flow for wind power used to generate hydrogen by electrolysis. The first process involved here is the application of kinetic energy from the wind on the wind generator to make alternating current (AC) power. The alternating current is delivered to an AC-to-DC converter, which converts the electricity to direct current. The conditioned rectified DC power is then applied through a DC-to-DC converter, where both voltage and current are adjusted to levels that exactly meet the needs of the electrolysis equipment. Consequently, the sufficiently conditioned DC power is then transferred to the electrolysis units, and it is applied in the splitting of water molecules into hydrogen and oxygen by the electrolysis of water molecules. This setup will offer an effective way to utilize renewable wind power to produce hydrogen, a clean and versatile energy carrier.

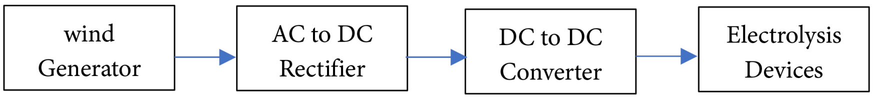


Figure 1. Block diagram hydrogen production.

3.1. Wind Energy

The energy harnessed from the motion of air at velocity V across a designated area A is expressed as $\rho A V$. Therefore,

$$\text{Power wind} = \frac{1}{2}\rho A V^3 (\text{W}) \quad (1)$$

whree,

ρ = air density (kg/m^3)

V = wind speed (m/s)

Wind energy is directly proportional to air density (ρ), the surface area exposed (A), and the cube of the wind speed (V^3). Air density, influenced by air pressure and temperature, is contingent upon the elevation above sea level.

$$\rho(z) = \frac{P_0}{(R \cdot T)\exp\left(-g \cdot \frac{z}{RT}\right)} \tag{2}$$

where,

$\rho(z)$ = air density as a function of altitude (kg/m^3)

P_0 = standard sea level atmospheric pressure (kg/m^3)

R = gas constant for air (J/K·mol)

T = temperature (K)

g = gravity constant (m/s^2)

z = altitude above sea level (m)

Wind power represents the energy available per unit of time in the wind. This energy is converted into mechanical rotational energy in the wind turbine rotor, which slows down the air mass. It's impossible to extract all wind power because doing so would stop the airflow in the turbine's path, creating congestion for incoming air masses.

3.2. Power Electronic Converter

Wind turbines generate alternating current (AC), which must be converted into direct current (DC) before electrolysis can produce hydrogen. This conversion process is necessary because electrolysis, which converts water molecules into hydrogen and oxygen, requires a constant DC input.

This conversion is carried out using a rectifier. A rectifier is a device that transforms alternating current to direct current by allowing electricity to flow in just one direction, generally using diodes. This rectification technique converts wind turbines' AC output into a stable DC form suited for electrolysis. The formula for rectification involves the use of diodes in a rectifier circuit. The instantaneous output voltage (V_{dc}) of a single-phase, half-wave rectifier can be given by the following equation:

$$V_{dc} = \frac{V_{\max}}{\pi} \tag{3}$$

Following rectification, a DC-DC converter is used to alter the voltage levels to meet the unique needs of the electrolysis system. The DC-DC converter is crucial to preserving the integrity of the DC supply, ensuring that it satisfies the appropriate voltage required for effective hydrogen generation or to ensure that the voltage supplied to the electrolyzer remains within its optimal operating range, improving system reliability and efficiency.

This converter works on magnetic field principles, allowing for exact voltage control while also providing a steady and stable DC input to the electrolysis process. The voltage transformation in a DC-DC converter can be mathematically expressed using the formula:

$$V_{out} = \frac{D}{1-d} \times V_{in} \tag{4}$$

3.3. Electrolysis Device

The electrolysis device converts direct current (DC) from a power source into a voltage suitable for splitting water molecules into hydrogen and oxygen. The chosen model operates effectively at stable voltage (~240 V) and pressure (~0.95 bar), suggesting it is designed for modular, low-pressure operation suited to renewable energy inputs. Its consistent performance across variable power inputs supports its suitability for wind-powered hydrogen generation. It operates with two electrodes, an anode (+) and a cathode (−), immersed in water. The anode connects to the positive terminal of the power supply, and the cathode connects to the negative terminal. Through this process, electrolysis produces green hydrogen and releases oxygen as a byproduct. The electrolysis of water involves two main electrochemical reactions occurring at the anode and cathode:

At the anode (oxidation)

$$2H_2O = O_2 + 4H^+ + 4e^- \tag{5}$$

At the cathode (reduction)

$$4H_2O + 4e^- = 2H_2 + 4OH^- \tag{6}$$

The overall reaction

$$2H_2O = 2H_2 + O_2 \tag{7}$$

3.4. Fuel Cell

With the hydrogen produced, the fuel cell now takes center stage. The fundamental principle of a hydrogen fuel cell involves the electrochemical conversion of hydrogen and oxygen into water, releasing electrical energy in the process. The overall reaction in a hydrogen fuel cell is:

$$2H_2 + O_2 = 2H_2O + \text{electric current} \tag{8}$$

Equation (8) encapsulates the core function of the fuel cell, where hydrogen gas at the anode undergoes oxidation to produce protons and electrons. Simultaneously, oxygen gas at the cathode accepts these electrons and combines with protons to form water. The electrons generated during the oxidation half-reaction travel through an external circuit, generating an electric current that can be harnessed for various applications.

4. Modeling and Simulation

Figure 2 illustrates the MATLAB/Simulink simulation setup, designed for modeling and simulating dynamic systems reliably. The simulation begins with the wind generator converting steady wind energy into alternating current (AC) electrical power. This AC power is then converted into direct current (DC) by the three-phase converter, essential for compatibility with the electrolysis. The DC-DC converter further regulates the DC power to meet the precise voltage and current requirements of the electrolyze. The electrolyze utilizes controlled DC power to perform electrolysis, splitting water into hydrogen and oxygen. Throughout this process, sensors continuously monitor electrical parameters such as current, voltage, and power output, providing real-time feedback. The control unit plays a critical role in overseeing and coordinating the entire system, adjusting parameters based on sensor data to ensure stable and efficient electricity supply to the electrolyze for optimal performance. Data analysis tools are integrated to gather and analyze performance data, facilitating comprehensive evaluations of system efficiency and effectiveness. This data-driven approach is crucial for identifying potential improvements and optimizing the system for superior performance.

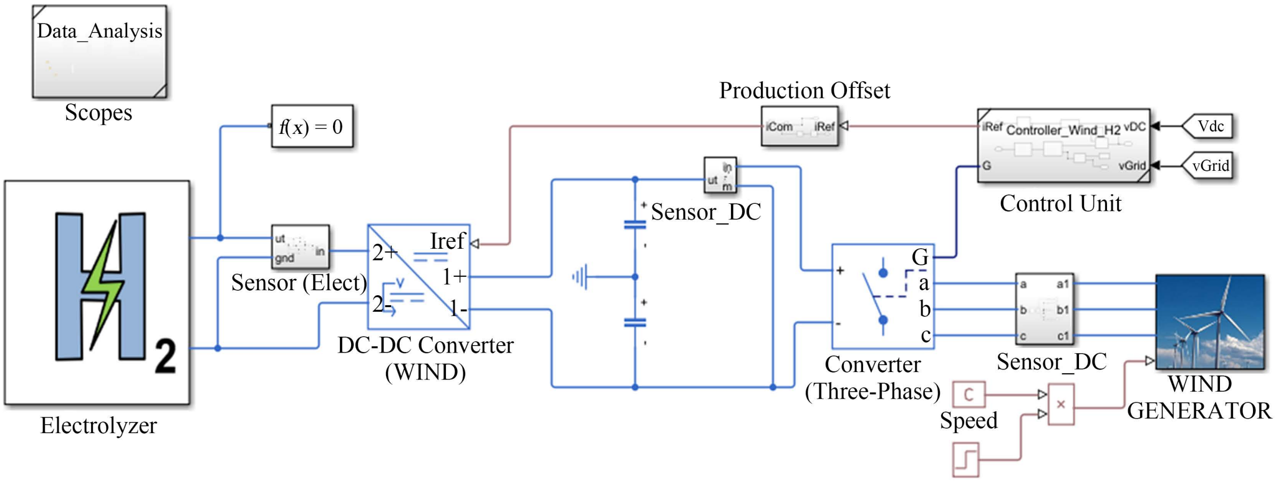


Figure 2. Overall simulation diagram.

5. Results

This study examines the feasibility of producing hydrogen through wind energy under the given parameter. Overall, the general objective of this research is to ascertain the effectiveness of the hydrogen production model through an evaluation of performances regarding different wind speeds. The characteristics of the wind turbine remain constant because RPM is the primary input due to simulation. Such research conducted in multiple locations with different wind speeds will collect all necessary information about the influence of location specific wind conditions on turbine performance and energy yield. Through this approach, the best possible configurations for achieving the maximum available efficiencies of practical operations of the turbines and maximum possible improvements can be identified.

5.1. Melaka

The first data is from Melaka, Malaysia. Table 1 presents the Wind Turbine Parameters for Simulation Study in Melaka, Malaysia.

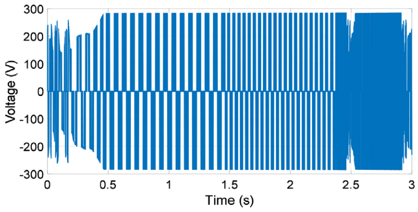
Table 1. Wind turbine parameters for simulation study in Melaka, Malaysia.

Parameter	Value
Rotor diameter (m)	80

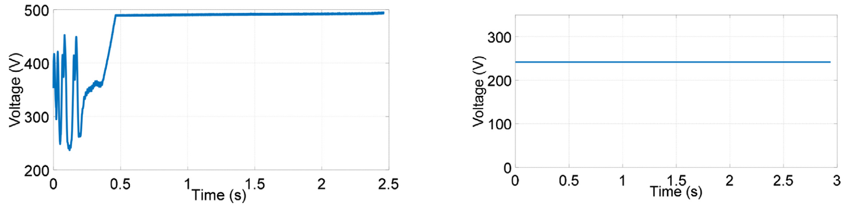
Continued

Wind speed (m/s)	1.75
Tip Speed Ration, (TSR)	7
RPM rotor (rpm)	2.924
Gear ratio	1:100
RPM Generator (rpm)	292.4

Figure 3 shows the Data Analysis of Hydrogen Production at Melaka, Malaysia.

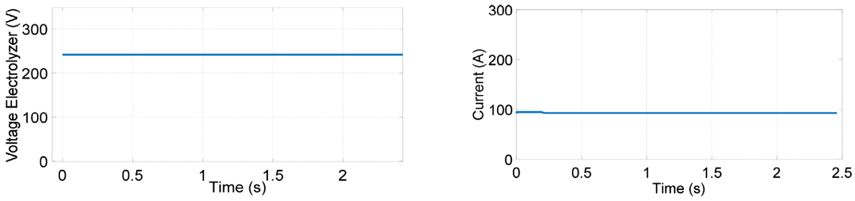


(a) Wind Generator to AC



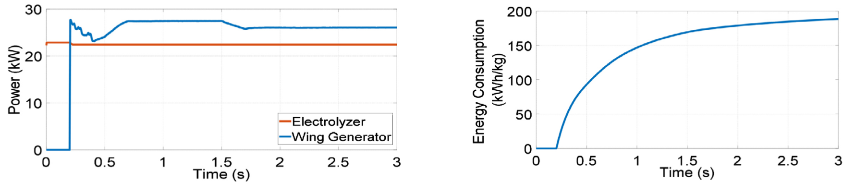
(b) AC to DC (Rectifier)

(c) DC to DC (Buck Boost)



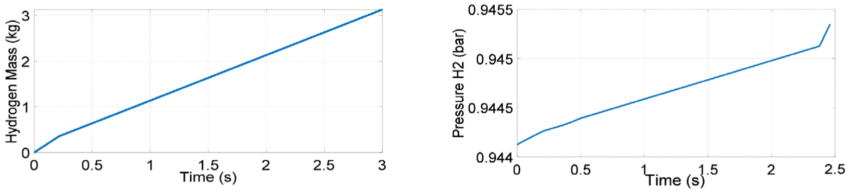
(d) Output Voltage Electrolyzer

(e) Output Current Electrolyzer



(f) Output Power

(g) Output Energy Consumption



(h) Output Hydrogen Mass

(i) Output Pressure H2

Figure 3. Data analysis of hydrogen production at Melaka, Malaysia.

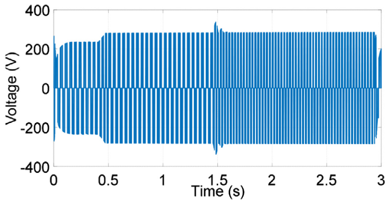
5.2. Kota Kinabalu

The second data is from Kota Kinabalu, Malaysia. Table 2 presents the Wind Turbine Parameters for Simulation Study in Kota Kinabalu, Malaysia.

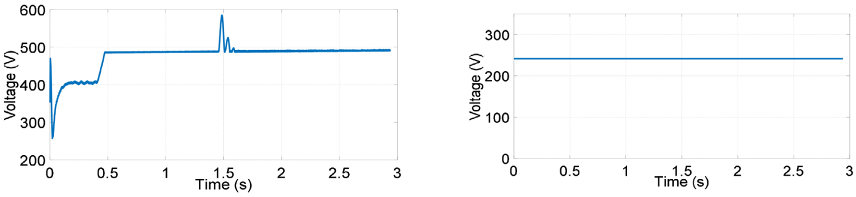
Table 2. Wind turbine parameters for simulation study in Kota Kinabalu, Malaysia.

Parameter	Value
Rotor diameter (m)	80
Wind speed (m/s)	2.8
Tip Speed Ration, (TSR)	7
RPM rotor (rpm)	4.679
Gear ratio	1:100
RPM Generator (rpm)	467.9

Figure 4 shows the Data Analysis of Hydrogen Production at Kota Kinabalu, Malaysia.

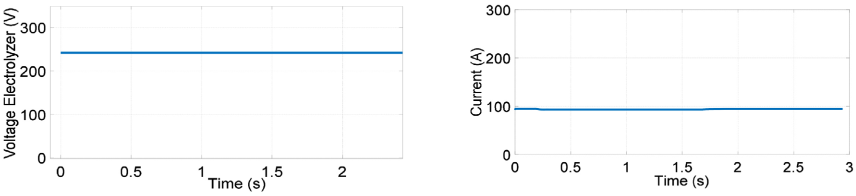


(a) Wind Generator to AC



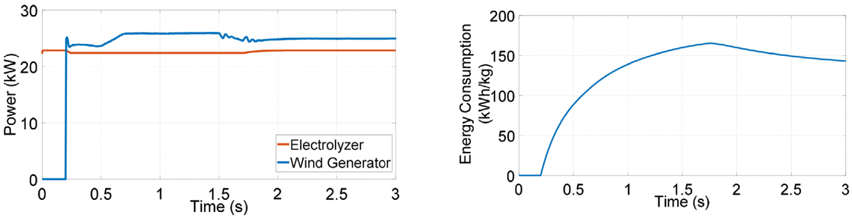
(b) AC to DC (Rectifier)

(c) DC to DC (Buck Boost)



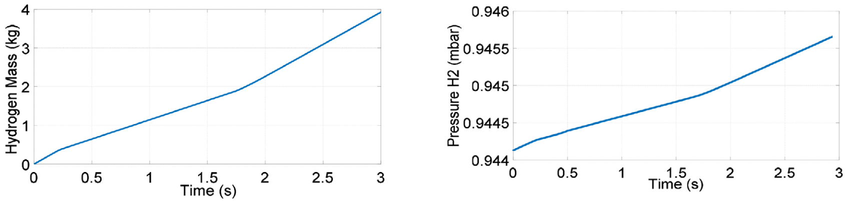
(d) Output Voltage Electrolyzer

(e) Output Current Electrolyzer



(f) Output Power

(g) Output Energy Consumption



(h) Output Hydrogen Mass

(i) Output Pressure H2

Figure 4. Data analysis of hydrogen production at Kota Kinabalu, Malaysia.

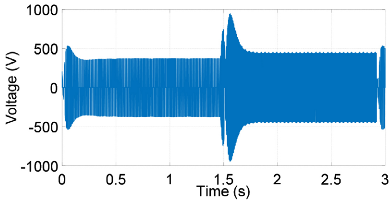
5.3. Tafila, Jordan

The third data is from Tafila, Jordan. Table 3 presents the Wind Turbine Parameters for Simulation Study in Tafila, Jordan.

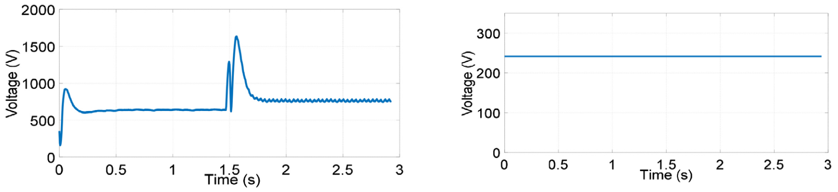
Table 3. Wind turbine parameters for simulation study in Tafila, Jordan.

Parameter	Value
Rotor diameter (m)	80
Wind speed (m/s)	8.5
Tip Speed Ration, (TSR)	7
RPM rotor (rpm)	14.20
Gear ratio	1:100
RPM Generator (rpm)	1420

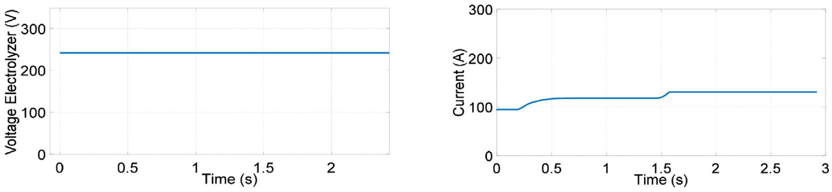
Figure 5 shows the Data Analysis of Hydrogen Production at Tafila, Jordan.



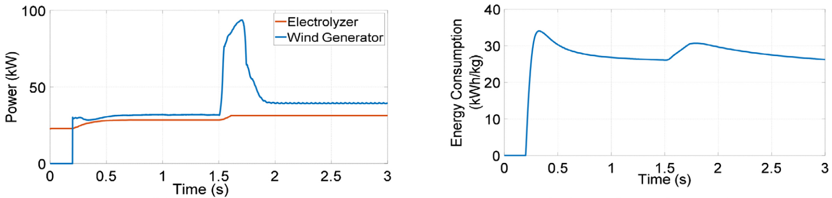
(a) Wind Generator to AC



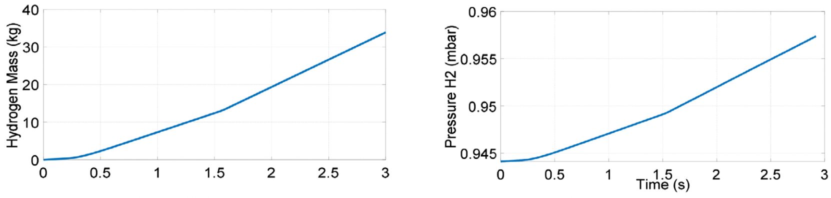
(b) AC to DC (Rectifier) (c) DC to DC (Buck Boost)



(d) Output Voltage Electrolyzer (e) Output Current Electrolyzer



(f) Output Power (g) Output Energy Consumption



(h) Output Hydrogen Mass (i) Output Pressure H2

Figure 5. Data analysis of hydrogen production at Tafila, Jordan.

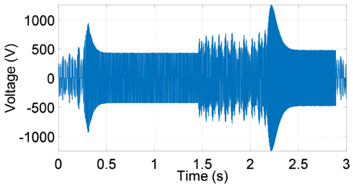
5.4. Gansu, China

The fourth data is from Gansu, China. **Table 4** presents the Wind Turbine Parameters for Simulation Study in Gansu, China.

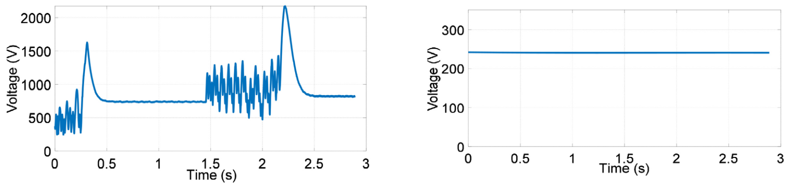
Table 4. Wind turbine parameters for simulation study in Gansu, China.

Parameter	Value
Rotor diameter (m)	80
Wind speed (m/s)	12
Tip Speed Ration, (TSR)	7
RPM rotor (rpm)	20.05
Gear ratio	1:100
RPM Generator (rpm)	2005

Figure 6 shows the Data Analysis of Hydrogen Production at Gansu, China.

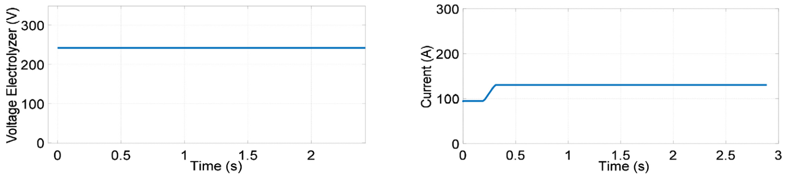


(a) Wind Generator to AC



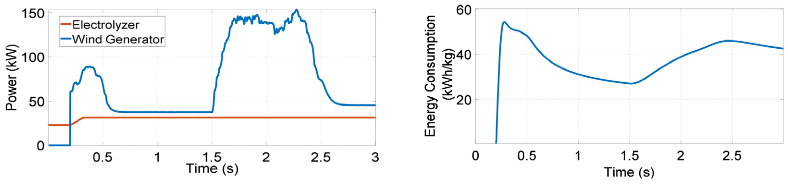
(b) AC to DC (Rectifier)

(c) DC to DC (Buck Boost)



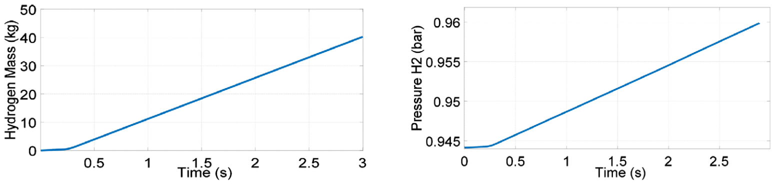
(d) Output Voltage Electrolyzer

(e) Output Current Electrolyzer



(f) Output Power

(g) Output Energy Consumption



(h) Output Hydrogen Mass

(i) Output Pressure H2

Figure 6. Data analysis of hydrogen production at Tafila, Jordan.

The data in Table 5 demonstrates the relationship between wind speed and hydrogen production efficiency across various system components for 4 cases.

Table 5. Relationship between wind speed and hydrogen production efficiency across various system components for 4 cases.

Wind speed (m/s)	Wind Generator		Rectifier	Buck Boost	Electrolyze				
	VAC (V)	Power (kW)	VDC (V)	VDC (V)	Voltage (V)	Energy Consumption (kWh/kg)	Hydrogen Mass (kg)	Pressure H2 (bar)	Power (kW)
1.75	204.6	26.05	493.6	241.5	241.5	136.51	1.5	0.945	22.4
2.80	210.5	24.95	491.3	241.5	241.5	120.24	2.0	0.945	22.8
8.50	361.9	39.35	769.9	240.6	240.6	26.29	15.0	0.953	31.3
12.0	393.2	45.50	817.9	240.6	240.6	35.29	20.0	0.953	31.3

At lower wind speeds, such as 1.75 m/s, the wind generator produces 22.4 kW of power. The electrolyze requires 136.51 kWh/kg to produce 1.5 kg of hydrogen under these conditions, with a resulting power output of 22.4 kW at 0.945 bar pressure. As wind speed increases to 2.80 m/s, power output improves slightly to 22.8 kW, reducing energy consumption to 120.24 kWh/kg and increasing hydrogen production to 2.0 kg.

At a moderate wind speed of 8.50 m/s, the wind generator ramps up to 39.35 kW, stabilizing the electrolyzed voltage at 240.6 VDC. This results in a significant drop in energy consumption to 26.29 kWh/kg, producing 15.0 kg of hydrogen with a power output of 31.3 kW.

At the highest wind speed of 12.0 m/s, the wind generator achieves 45.50 kW output, maintaining steady electrolyze efficiency. Energy consumption further decreases to 35.29 kWh/kg while producing 20.0 kg of hydrogen, with a constant power output of 31.3 kW. Overall, the data highlights that as wind speed increases, the system's efficiency improves, characterized by reduced energy consumption per kilogram of hydrogen produced. This indicates the system's capability to effectively handle higher power inputs while maintaining efficiency in hydrogen production.

5.5. Summary

The sensitivity of hydrogen production outputs to different wind speeds underscores the importance of optimizing system parameters for enhanced efficiency. Lower wind speeds typically result in higher energy consumption and lower hydrogen yields, whereas moderate to high wind speeds enhance overall system performance.

Future research should focus on developing optimal configurations for electrolyzes tailored to variable wind conditions. This entails exploring advanced materials and technologies that can boost system efficiency. Real-time monitoring coupled with adaptive control systems will be crucial in leveraging fluctuating renewable energy sources effectively for hydrogen production. By addressing these areas, advancements can be made towards achieving more sustainable energy solutions that harness wind power efficiently for green hydrogen production.

6. Conclusions

The study successfully created and verified a complete model for hydrogen synthesis from wind energy, demonstrating its promise as a clean and renewable energy source. This initiative addresses the rising need for clean hydrogen in accordance with Sustainable Development Goal 7: Affordable and Clean Energy.

Key simulation studies demonstrated the efficiency and cost-effectiveness of using wind energy to produce hydrogen. Moderate wind speeds were found to optimize energy usage and hydrogen output, demonstrating the model's usefulness under various situations, while higher wind speeds lead to greater hydrogen yield and improved energy efficiency (lower kWh/kg). This strong correlation from the results suggests that selecting sites with higher and more consistent wind speeds can significantly enhance the energy efficiency and hydrogen output of wind-to-hydrogen systems.

This study has made considerable progress by developing an improved, dependable, and scalable hydrogen generation model based on electrolysis, assuring an ecologically beneficial process with no CO_2 emissions. This places the created model as a critical contribution to the advancement of green hydrogen technology, aiding global efforts to battle climate change and reduce dependency on fossil fuels.

Overall, the findings of this study are favorable to the integration of renewable energy sources into hydrogen production systems. The model not only lays the groundwork for future optimization, but it also indicates the feasibility of moving to a sustainable, low-carbon energy future. In conclusion, the study successfully demonstrated the feasibility and efficacy of manufacturing hydrogen using wind energy, setting the framework for future advances in this crucial sector and emphasizing the necessity of renewable energy integration in global sustainability efforts.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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