Modeling and Simulation of Renewable Energy-Based Green Hydrogen Production Using Solar PV and Wind Systems

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Abstract

Hydrogen is increasingly being explored for various industrial applications, including the production of ammonia and methanol. However, conventional hydrogen production methods are heavily dependent on fossil fuels and are associated with significant environmental emissions. To address these challenges, renewable energy sources such as solar photovoltaics (PV) and wind turbines (WT) have emerged as sustainable alternatives for green hydrogen production. This study focuses on enhancing hydrogen generation by effectively utilizing and storing energy derived from renewable sources.One of the major challenges in renewable energy systems is the need for efficient and cost-effective energy storage solutions. Integrating renewable energy with hydrogen production through electrolysis provides a promising pathway to overcome intermittency issues and improve overall system efficiency. In this work, a theoretical model of a caustic electrolyzer connected to both a solar PV system and a wind energy conversion system is developed and analyzed.The study evaluates the input and output power characteristics of both solar and wind systems and investigates their impact on hydrogen production rates. Maximum Power Point Tracking (MPPT) is employed to ensure optimal energy extraction from the PV system, while appropriate control strategies are used for wind energy conversion. The complete system is modeled and simulated in the MATLAB/Simulink environment. Simulation results demonstrate that the proposed renewable-based hydrogen production system operates efficiently under varying environmental conditions. The findings highlight the effectiveness of integrating solar and wind energy with electrolysis for green hydrogen generation, offering a reliable and sustainable solution for future energy needs.

Index Terms **-Solar, Wind energy conversion system, Grid-connected renewable energy,Water electrolyser,H2,Green Hydrogen**

I.INTRODUCTION

The rapid growth of global energy demand and environmental concerns have encouraged the adoption of renewable energy systems. Conventional fossil fuel-based energy generation contributes significantly to greenhouse gas emissions. Renewable sources such as solar and wind energy provide sustainable alternatives. Hydrogen produced through renewable energy powered electrolysis is considered green hydrogen and is gaining significant attention as a clean energy carrier.
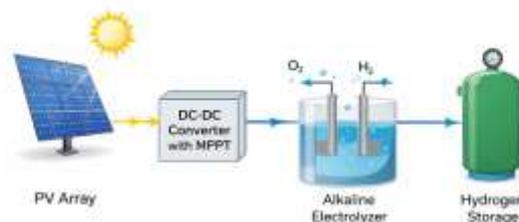

Figure 1: Conceptual diagram of solar powered hydrogen production

The conceptual diagram illustrates the process of producing hydrogen using solar energy through water electrolysis. In this system, solar radiation from the sun is captured by the photovoltaic (PV) array, which converts sunlight directly into electrical energy. Since the output power of the PV system varies with solar irradiance and temperature, a DC–DC converter equipped with a Maximum Power Point Tracking (MPPT) controller is used. The MPPT ensures that the PV array operates at its maximum power point so that the maximum available solar energy can be extracted.

The regulated electrical power from the DC–DC converter is then supplied to the water electrolyzer. The electrolyzer performs the electrochemical process of splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) gases. When electrical current passes through the water with the help of electrodes and an electrolyte, hydrogen is produced at the cathode while oxygen is released at the anode. This process is environmentally friendly when powered by renewable sources, because it produces no carbon emissions.

The generated hydrogen gas is collected and stored in a hydrogen storage tank for later use. Stored hydrogen can be utilized in various applications such as electricity generation through fuel cells, transportation fuel, or industrial processes. By integrating solar energy with electrolysis technology, the system enables sustainable and clean hydrogen production, which plays an important role in future renewable energy systems and energy storage solutions.

II. LITERATURE REVIEW

Several studies have investigated renewable-based hydrogen production systems using different electrolyzer technologies and control strategies. Solar photovoltaic systems have been widely studied for decentralized hydrogen generation due to their modular structure. Wind energy systems offer higher capacity factors and enable continuous hydrogen production. Hybrid renewable systems combining solar and wind sources have been proposed to improve reliability and system efficiency.

Hydrogen production using renewable energy sources has received significant attention in recent years due to the growing demand for clean and sustainable energy systems. Traditional hydrogen production methods such as steam methane reforming rely heavily on fossil fuels and produce large amounts of carbon dioxide emissions. To overcome these environmental concerns, researchers have focused on green hydrogen production using renewable energy–driven water electrolysis. Studies have shown that electrolysis powered by renewable sources such as solar and wind energy provides a clean and environmentally friendly method for hydrogen generation.

Several researchers have investigated solar photovoltaic (PV) systems integrated with electrolyzers for hydrogen production. Solar energy is widely available and suitable for decentralized hydrogen generation systems. Previous studies demonstrate that the use of power electronic converters with Maximum Power Point Tracking (MPPT) algorithms significantly improves the efficiency of PV-based hydrogen production systems. However, solar energy suffers from intermittency due to variations in solar irradiance, weather conditions, and the absence of sunlight during nighttime.

Wind energy has also been widely explored as a reliable renewable energy source for hydrogen production. Wind turbines can generate electricity during both day and night, often achieving higher capacity factors than solar PV systems. Researchers have proposed hybrid renewable energy systems that combine solar and wind sources to overcome the limitations of individual renewable resources. Hybrid systems improve energy availability, reduce power fluctuations, and enhance the overall reliability of hydrogen production systems. These studies highlight the importance of integrating renewable energy technologies with efficient electrolysis systems for sustainable hydrogen generation.

III. RENEWABLE ENERGY BASED HYDROGEN PRODUCTION SYSTEM

The proposed system integrates solar photovoltaic and wind energy sources with an alkaline electrolyzer for hydrogen production. Power electronic converters and MPPT controllers ensure maximum power extraction and stable operation of the electrolyzer. Hydrogen produced through electrolysis is stored in a compressed hydrogen storage tank.
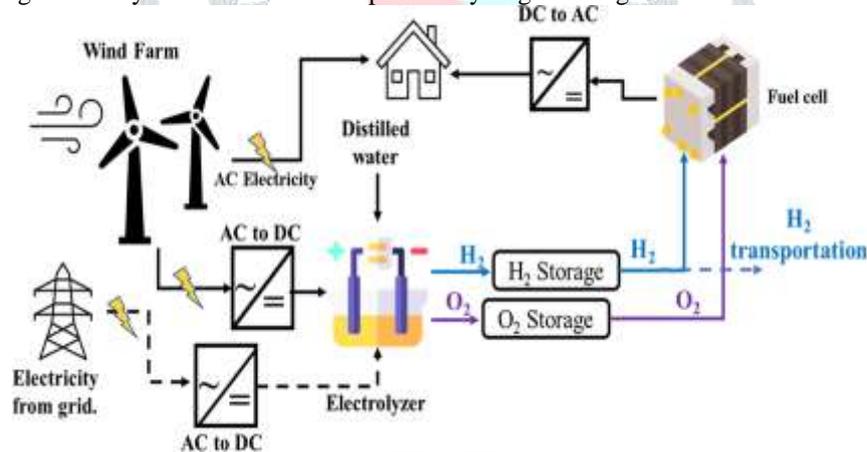

Figure 2: Wind energy based hydrogen production system

The wind energy–based hydrogen production system converts the kinetic energy of wind into electrical energy and uses it to produce hydrogen through water electrolysis. In this system, a wind turbine captures the kinetic energy from moving air and converts it into mechanical energy through the rotation of its blades. This mechanical energy drives an electrical generator, typically a permanent magnet synchronous generator (PMSG), which produces alternating current (AC) electricity. Since the output of the generator varies depending on wind speed, power electronic converters are required to regulate the electrical power.

The generated AC power is first converted into direct current (DC) using an AC–DC rectifier. After rectification, a DC–DC converter with a Maximum Power Point Tracking (MPPT) controller is used to optimize the power extraction from the wind turbine. The MPPT algorithm adjusts the operating point of the turbine–generator system to ensure maximum energy capture under varying wind conditions. The regulated DC power is then supplied to the electrolyzer, which requires stable voltage and current for efficient operation.

Inside the electrolyzer, water molecules are split into hydrogen and oxygen through the electrolysis process. Hydrogen gas is produced at the cathode while oxygen is released at the anode. The produced hydrogen is then collected and stored in a hydrogen storage tank for later use in applications such as fuel cells, power generation, or transportation. Wind-powered hydrogen

production provides a sustainable method for converting renewable wind energy into a clean and storable energy carrier
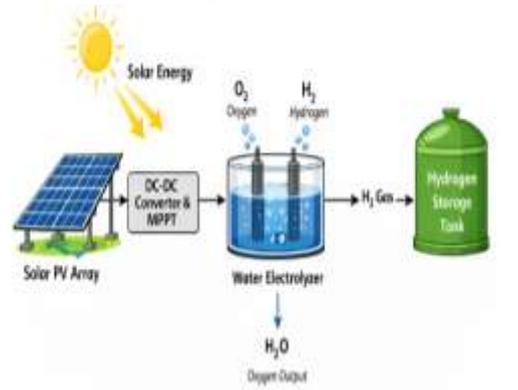

Figure 3: Solar PV–electrolyzer system configuration

This figure shows the configuration of a solar photovoltaic (PV) system integrated with a water electrolyzer for hydrogen production. In this system, the solar PV array converts sunlight into direct current (DC) electrical energy. The amount of electrical power produced by the PV panels depends on solar irradiance and environmental conditions such as temperature. Because the PV output varies throughout the day, a DC–DC converter with a Maximum Power Point Tracking (MPPT) controller is used to ensure that the solar panels operate at their optimal power point.

The DC–DC converter regulates the voltage and current supplied from the PV array to the electrolyzer. The MPPT algorithm continuously adjusts the converter duty cycle to extract the maximum available power from the solar panels. This power conditioning stage is important because the electrolyzer requires a stable and controlled DC input to operate efficiently and safely.

The regulated electrical energy is then supplied to the water electrolyzer, where the electrolysis process occurs. Water molecules are split into hydrogen and oxygen gases when an electric current passes through the electrolyte solution. Hydrogen gas is collected and stored in a hydrogen storage tank, while oxygen is released as a byproduct. This configuration enables clean hydrogen production using renewable solar energy and contributes to sustainable energy storage and utilization.
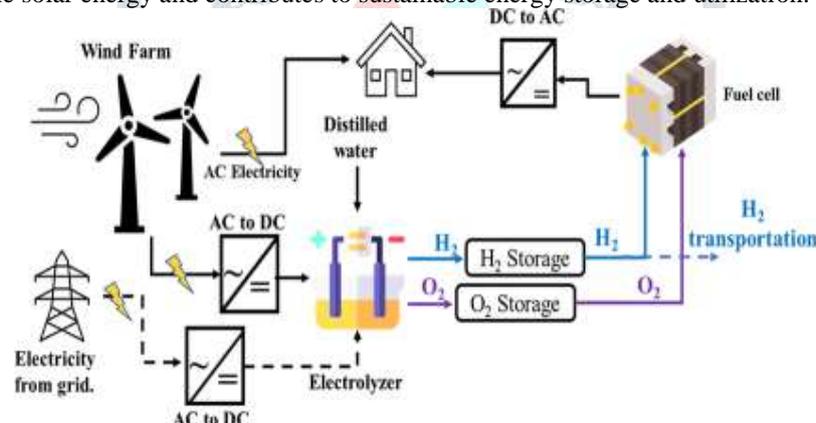

Figure 4: Wind turbine hydrogen production configuration

This figure illustrates the configuration of a hydrogen production system powered by wind energy. In this system, a wind turbine captures the kinetic energy of moving air and converts it into mechanical energy through the rotation of turbine blades. The rotating shaft drives an electrical generator, typically a permanent magnet synchronous generator (PMSG), which converts mechanical energy into alternating current (AC) electrical power. Since wind speed varies continuously, the electrical output of the generator also fluctuates.

The generated AC power is converted into direct current (DC) using an AC–DC rectifier. After rectification, a DC–DC converter with a Maximum Power Point Tracking (MPPT) controller is used to regulate the electrical power and ensure maximum energy extraction from the wind turbine. The MPPT controller adjusts the operating conditions of the turbine–generator system to maintain optimal power output under varying wind speeds. This controlled DC power is then supplied to the electrolyzer.

The electrolyzer uses the supplied electrical energy to split water into hydrogen and oxygen through the electrolysis process. Hydrogen gas is produced at the cathode, while oxygen is released at the anode. The generated hydrogen is collected and stored in a hydrogen storage tank for future use in applications such as fuel cells, electricity generation, or transportation fuel. This configuration demonstrates how wind energy can be converted into a clean and storable energy carrier in the form of hydrogen.
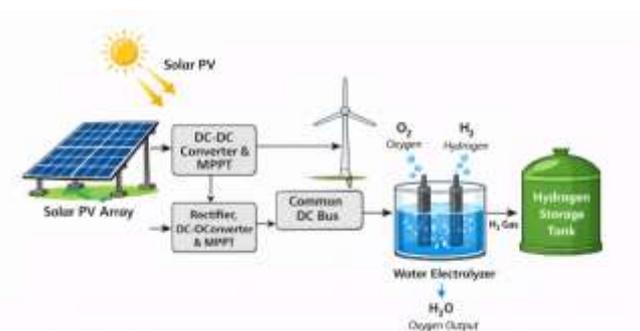
Figure 5: Hybrid solar–wind hydrogen production system

This figure illustrates a hybrid renewable energy system that combines solar photovoltaic (PV) and wind energy sources for hydrogen production through water electrolysis. In this configuration, the solar PV array converts sunlight into electrical energy, while the wind turbine converts the kinetic energy of wind into mechanical energy and then into electrical energy through a generator. Since the electrical outputs of these renewable sources vary depending on environmental conditions, power electronic converters are used to regulate and control the generated power.

The electricity generated from the solar PV system passes through a DC–DC converter equipped with a Maximum Power Point Tracking (MPPT) controller to ensure maximum energy extraction from solar panels. Similarly, the electrical power generated by the wind turbine is converted and conditioned using a rectifier and DC–DC converter with MPPT control. The regulated outputs from both renewable sources are connected to a common DC bus, which acts as a central point for integrating and managing the electrical power from the solar and wind subsystems.

The combined DC power from the common DC bus is supplied to the water electrolyzer, where the electrolysis process splits water into hydrogen and oxygen gases. Hydrogen gas produced at the cathode is collected and stored in a hydrogen storage tank for future use, while oxygen is released as a byproduct. By combining solar and wind energy, the hybrid system improves energy availability and reduces the intermittency associated with individual renewable sources, resulting in more stable and efficient hydrogen production.

IV. SYSTEM MODELING

The modeling of the hydrogen production system includes photovoltaic system modeling, wind energy conversion modeling, alkaline electrolyzer modeling, DC–DC converter modeling, and hydrogen storage system modeling. Mathematical models are used to analyze system performance and efficiency under different renewable energy conditions.

The proposed system is designed to produce green hydrogen by integrating renewable energy sources with an alkaline water electrolyzer using suitable power electronic converters and control strategies. Solar photovoltaic (PV) and wind energy are selected as the primary renewable sources due to their availability and complementary characteristics. The system focuses on maximizing renewable energy utilization while ensuring stable and efficient hydrogen production. Power electronic interfaces such as AC–DC rectifiers and DC–DC converters are used to regulate the electrical power supplied to the electrolyzer.

The overall system consists of a solar PV array, wind turbine with generator, power electronic converters, MPPT controllers, an alkaline electrolyzer, and a hydrogen storage tank. Both renewable energy sources are connected to a common DC bus, which acts as the central power interface. The PV subsystem uses a DC–DC converter with Maximum Power Point Tracking (MPPT) control to extract maximum power from solar panels, while the wind subsystem uses a rectifier and DC–DC converter with MPPT to regulate the wind generator output. This arrangement ensures efficient power conditioning and stable supply to the electrolyzer.

The electrolyzer converts electrical energy into chemical energy by splitting water into hydrogen and oxygen. The produced hydrogen is collected and stored in a compressed hydrogen storage tank for later use. The system can operate in solar-only mode, wind-only mode, or hybrid mode depending on the availability of renewable energy sources. Hybrid operation improves system reliability and reduces the effect of renewable energy intermittency, enabling continuous and efficient hydrogen production.
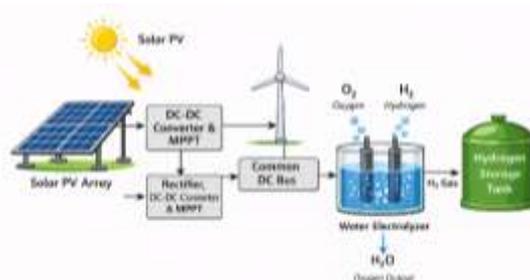

Figure: 6 Overall block diagram of the proposed renewable-based hydrogen production system.

V.Results

Green_solar–battery–hydrogen system

The simulation results of the solar–battery–hydrogen system demonstrate effective integration and coordination between renewable generation, energy storage, and hydrogen production. The solar array, driven by a time-varying irradiance profile over a 24-hour period, produces power that closely follows the available sunlight. The implementation of the Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P&O) technique ensures that the solar system operates near its optimal point, thereby maximizing energy extraction. Although minor oscillations are observed due to the inherent nature of the P&O algorithm, the overall performance remains stable and efficient.
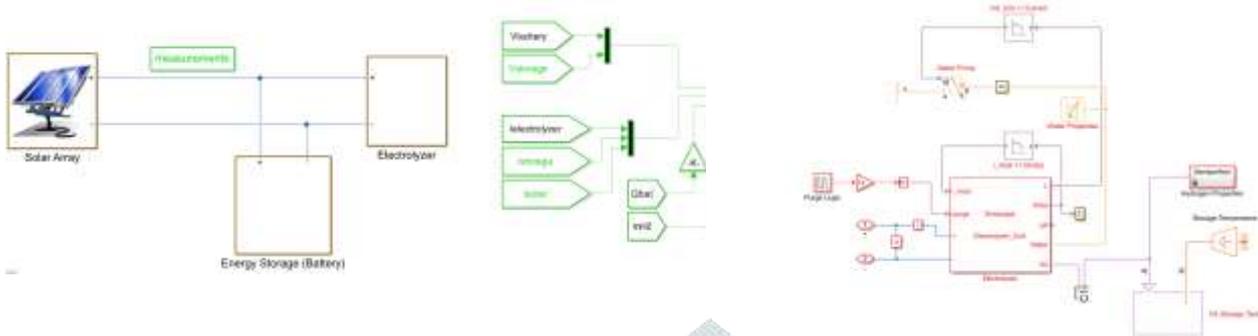

Fig:6 Simulink for Green_solar–battery–hydrogen system

The battery energy storage system plays a crucial role in stabilizing the power flow. During periods of high solar generation, excess energy is stored in the battery, while during low irradiance conditions, the battery discharges to support the system. The DC-DC converter effectively regulates the charging and discharging process, maintaining voltage within safe operating limits. This behavior confirms that the battery acts as a reliable short-term energy buffer, reducing fluctuations and ensuring continuity of supply.

The electrolyzer subsystem efficiently utilizes surplus electrical energy to produce hydrogen. As solar power exceeds the immediate demand and battery storage capacity, the excess energy is diverted to the electrolyzer, where water is split into hydrogen and oxygen. The hydrogen production rate increases with input current and is influenced by thermal conditions within the system. The generated hydrogen is then stored in a tank, where its behavior is modeled using semiperfect gas properties, accounting for variations in temperature and pressure. This allows the system to realistically simulate hydrogen storage dynamics and long-term energy retention .
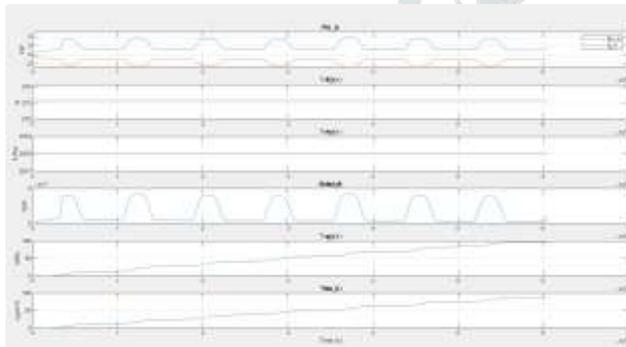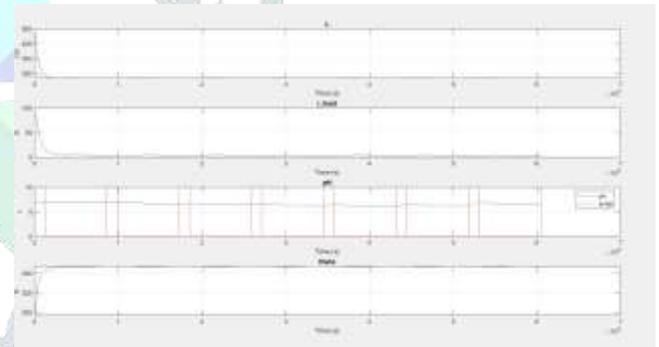

Fig:7 Scope for H2 storage

Fig:8 Scope for Electrolyzer

Furthermore, the system incorporates a comprehensive measurement framework that monitors key parameters such as solar power, battery voltage and current, electrolyzer input, and hydrogen output. Energy quantities are calculated using discrete-time integration, enabling accurate tracking of energy generation, consumption, and storage over time. This provides valuable insights into system efficiency and performance.

Overall, the results indicate that the hybrid system effectively manages energy by prioritizing battery storage for short-term needs and utilizing hydrogen production for long-term storage. This dual-storage strategy enhances system reliability and ensures optimal use of renewable resources. Despite minor limitations such as MPPT-induced oscillations and simplified electrolyzer efficiency modeling, the system demonstrates strong potential for applications in microgrids and standalone renewable energy systems.

Green_H2_Solar

The simulation results of the **Green_H2_Solar_Only** system demonstrate the effective operation of a solar-driven hydrogen production model with integrated sensing and energy tracking. As shown in the *overall system diagram on page 1*, the solar photovoltaic array supplies electrical energy that is conditioned through a DC-DC converter and directed toward the electrolyzer unit for hydrogen generation . The system successfully captures the dynamic relationship between solar irradiance and power generation, where variations in irradiance directly influence the electrical output of the photovoltaic panels. This behavior is further supported by the irradiance input defined in the model, which varies between 720 W/m² and 1200 W/m², as indicated in the *table on page 5*, ensuring realistic operating conditions.

The MPPT-based control strategy embedded within the system enables efficient extraction of solar energy. By continuously adjusting the operating point of the PV array, the controller maintains near-optimal performance under changing environmental conditions. As a result, the electrical power supplied to the electrolyzer remains stable, with only minor fluctuations due to control dynamics. This contributes to improved overall system efficiency and minimizes energy losses.
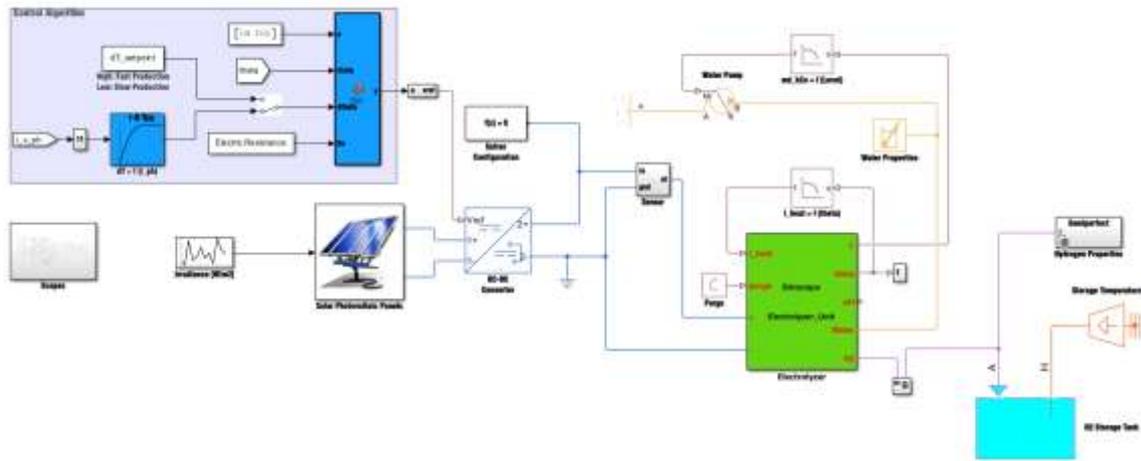
Fig:**9 Green_H2_Solar**

The electrolyzer subsystem plays a central role in converting electrical energy into hydrogen. Based on the *electrolyzer configuration shown on page 3*, the system models electrical, thermal, and fluid interactions to simulate hydrogen production accurately . The hydrogen generation rate increases proportionally with the input current, confirming that higher solar availability leads to increased hydrogen output. Additionally, the inclusion of thermal effects and water flow dynamics enhances the realism of the model, as these factors influence the efficiency and stability of the electrolysis process.
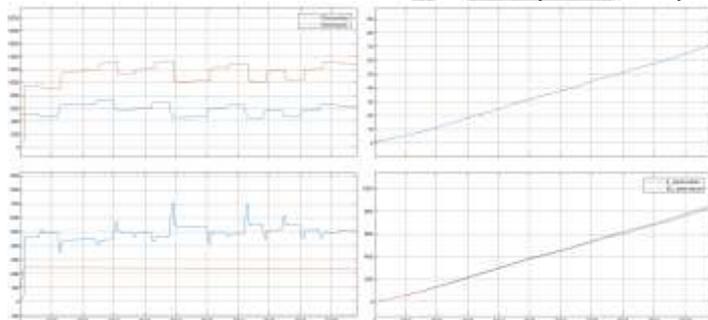

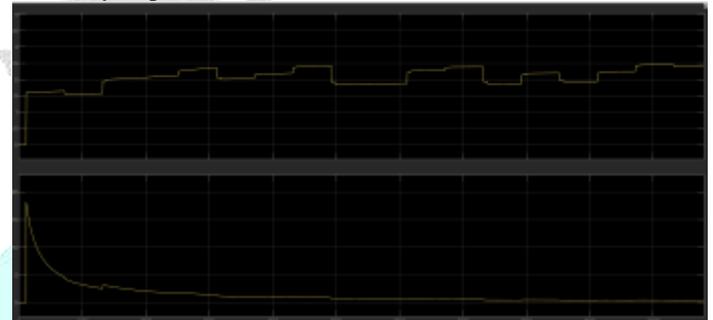**Fig:10 Scopes for Green_H2_Solar**   **Fig:11 Scopes for electrolyser**

Hydrogen storage behavior is also effectively represented in the model. The produced hydrogen is stored in a tank whose properties, including volume and temperature, are defined in the system parameters, as seen in the *model variables table on page 11* . The storage system accounts for gas dynamics using semiperfect hydrogen properties, allowing for accurate representation of pressure and temperature variations. This ensures that the system can simulate long-term energy storage reliably.

The measurement and monitoring subsystem provides detailed insights into system performance. As illustrated in the *sensor and scopes sections on pages 6 and 5*, parameters such as voltage, current, power, hydrogen mass flow rate, and energy are continuously measured and processed . The integration of these signals enables the calculation of total energy generated and consumed, facilitating performance evaluation and validation of the model.

Overall, the results indicate that the system operates efficiently under varying solar conditions, successfully converting solar energy into hydrogen while maintaining stable performance. The integration of control algorithms, physical modeling, and measurement systems ensures accurate simulation of real-world behavior. However, minor limitations such as control-induced oscillations and simplified efficiency modeling suggest that further optimization could enhance system performance. Despite these limitations, the model demonstrates strong potential for renewable energy applications, particularly in standalone hydrogen production and microgrid systems.

Simuation for Wind_PMSG_Electrolyzer

The simulation results of the **Wind_PMGen_ELE** system demonstrate the effective conversion of wind energy into electrical power and its subsequent utilization for hydrogen production through an electrolyzer. As illustrated in the *overall system diagram* , the Permanent Magnet Synchronous Generator (PMSG) is driven by wind input and generates three-phase AC power, which is then rectified and regulated before being supplied to the electrolyzer . This configuration validates the feasibility of integrating wind energy systems with hydrogen production units for renewable energy applications.
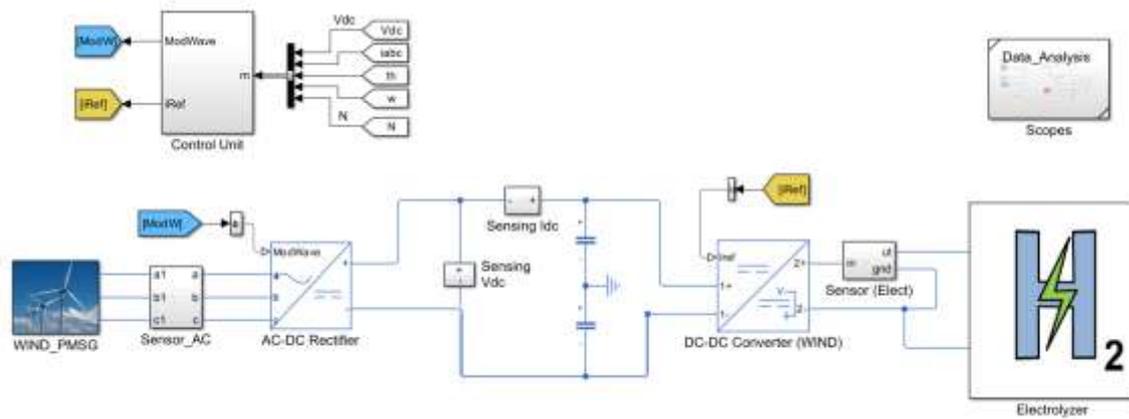
Fig:12 Simulink for Wind_PMSG_Electrolyser

The AC-DC rectifier and DC-DC converter stages play a crucial role in stabilizing the output power. From the *system representation* the rectifier converts variable-frequency AC from the PMSG into DC, while the DC-DC converter regulates the voltage according to the system requirements . The presence of sensing blocks for DC voltage (Vdc) and current (Idc) ensures continuous monitoring and feedback, which contributes to maintaining a stable DC link. The results indicate that despite fluctuations in wind speed, the converter successfully maintains a relatively constant DC output suitable for electrolysis.

The Field Oriented Control (FOC) strategy implemented in the control unit enhances system performance. As shown in the *control architecture on pages 5–7*, the controller regulates generator currents using dq-axis transformations and a current control loop . The outer loop control adjusts torque and speed references based on system conditions. This control mechanism ensures efficient energy extraction from the wind turbine and minimizes oscillations in electrical output. The inclusion of PWM-based switching further improves the dynamic response of the system.

The electrolyzer subsystem effectively converts electrical energy into hydrogen. According to the *electrolyzer model*, the system incorporates thermal dynamics, water flow control, and hydrogen storage mechanisms . The hydrogen production rate is directly influenced by the input current supplied from the DC-DC converter. As wind speed increases, the generated electrical power rises, leading to higher hydrogen production rates. The integration of semiperfect hydrogen properties and storage tank modeling allows realistic simulation of pressure and temperature variations within the storage system.
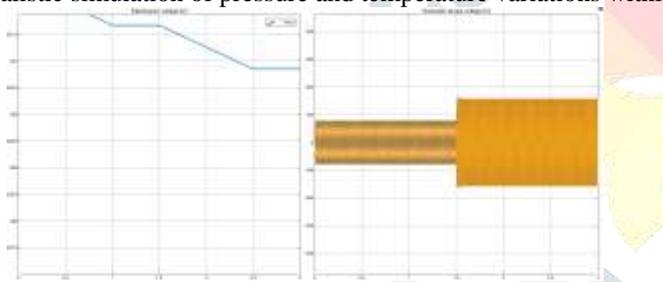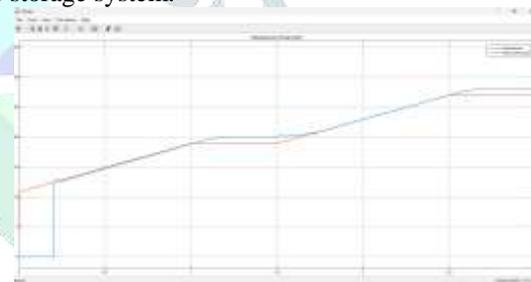

Fig:13 Scopes for voltage

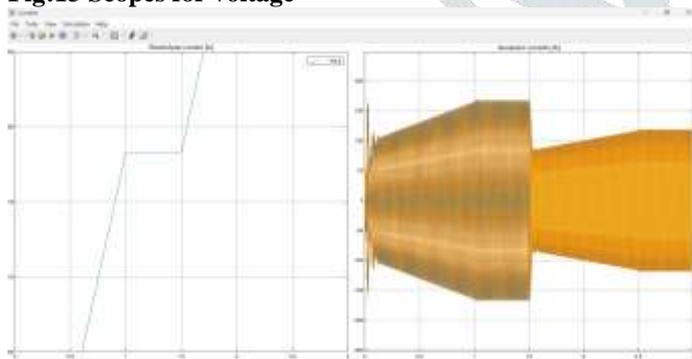**Fig:14 Scopes for Elctrolyzer power**

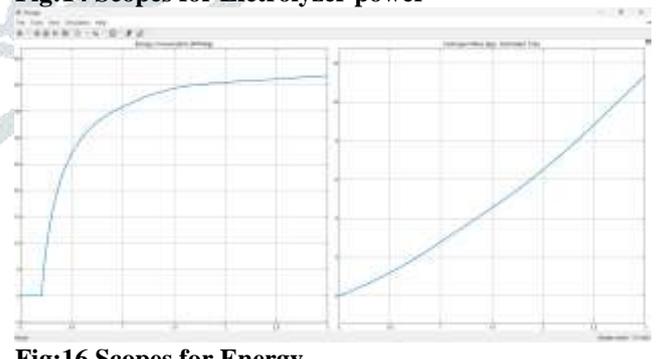**Fig:15 Scopes for Current**

Fig:16 Scopes for Energy

Measurement and sensing components provide detailed insights into system behavior. The *sensor configurations* show that voltage, current, power, and hydrogen flow parameters are continuously monitored . These measurements are processed using MATLAB function blocks and converters to evaluate system efficiency and performance. The results confirm that the sensing system accurately captures transient and steady-state responses, enabling proper validation of the model.

Overall, the simulation demonstrates that the wind-driven hydrogen production system operates reliably under varying conditions. The coordinated operation of the PMSG, power electronic converters, and control algorithms ensures stable power delivery to the electrolyzer. However, minor fluctuations in DC voltage and current are observed due to wind variability and switching dynamics. These can be further minimized by optimizing controller parameters or incorporating energy storage elements.

Conclusion

The collection of developed models—covering **solar-based hydrogen production**, **wind-driven hydrogen generation**, and **hybrid energy storage systems integrating battery and electrolyzer units**—collectively demonstrate a comprehensive and

practical approach toward renewable energy utilization and green hydrogen production. Across all systems, renewable sources such as solar irradiance and wind energy are effectively converted into electrical power and further utilized for hydrogen generation, highlighting the feasibility of sustainable, emission-free energy solutions.

The solar-based models show that the use of MPPT techniques enables efficient extraction of energy under varying irradiance conditions, ensuring maximum utilization of available solar power. Similarly, the wind energy system using a Permanent Magnet Synchronous Generator (PMSG) with Field Oriented Control (FOC) demonstrates stable and efficient energy conversion despite fluctuations in wind speed. In both cases, power electronic converters play a critical role in conditioning and regulating the generated power to meet system requirements.

A key strength observed across all models is the integration of hydrogen production through electrolyzers. The simulations confirm that hydrogen generation is directly dependent on the available electrical input, making it an effective method for storing excess renewable energy. The inclusion of thermal effects, fluid dynamics, and gas storage modeling enhances the realism of the systems and provides deeper insight into hydrogen production and storage behavior.

The hybrid system combining solar energy, battery storage, and hydrogen production further strengthens the overall performance by introducing a dual-storage mechanism. The battery acts as a short-term energy buffer, improving system stability and handling transient conditions, while hydrogen storage provides a long-term energy solution. This layered storage approach significantly enhances reliability and ensures continuous energy availability even under intermittent renewable conditions.

Additionally, all models incorporate detailed measurement and monitoring systems, enabling accurate tracking of voltage, current, power, and energy flow. These features support performance evaluation and validate the effectiveness of control strategies used throughout the systems.

In conclusion, the combined results from all simulations confirm that integrating renewable energy sources with hydrogen production and storage systems is a highly promising solution for future energy demands. While minor limitations such as control oscillations, converter losses, and simplified efficiency modeling exist, the overall system performance remains stable, efficient, and scalable. These models provide a strong foundation for further advancements in hybrid renewable energy systems, smart microgrids, and large-scale green hydrogen production technologies.

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