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Modelling and Optimization of a Grid-Integrated Hydrogen Energy Storage System for Renewable Energy Smoothing

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ABSTRACT:

The increasing penetration of renewable energy sources into the modern electrical power system has created significant issues of renewable intermittency, voltage instability and power fluctuation. The PV power generation is strongly influenced by environmental factors like irradiance and temperature, which leads to fluctuations in power output and can adversely impact grid stability and energy management. To overcome these challenges, this thesis proposes the modelling and optimization of a grid-integrated hydrogen energy storage system for smoothing renewable energy and delivering stable power. The proposed system consists of PV array, electrolyzer, hydrogen storage tank, fuel cell, DC bus, and grid interface in MATLAB/Simulink environment.

Mathematical models of the major system components were created to study the operational behavior of the integrated renewable-hydrogen system under different load and renewable generation scenarios. A rule-based optimization and energy management strategy was developed to optimize the hydrogen production and fuel cell operation based on the system demand. In times of excess PV generation, the surplus electricity is channeled to the electrolyzer, where it is used to generate hydrogen for long-duration storage. When renewable energy is in deficit, the fuel cell provides electricity to meet the load demand and stabilize the voltage of the DC bus.

The simulation results show that the proposed hydrogen-integrated system can successfully mitigate the fluctuations in renewable energy sources, increase the utilization of renewable energy, and enhance the reliability of the system. The integrated operation of the electrolyzer and fuel cell mitigated the intermittency effects of renewables, enhanced the voltage regulation of the DC bus, and minimized excess renewable energy curtailment. Moreover, the hydrogen storage system demonstrated a reliable long duration energy balancing capability, which was better than traditional short duration storage methods. The results show that hydrogen energy storage can effectively enhance the flexibility, stability and sustainability of future smart grid systems with high penetration of renewable energy, and provide efficient management of renewable energy and grid support operation.

KEYWORDS: Hydrogen Energy Storage, Renewable Energy Smoothing, Grid-Integrated Energy Systems, PV Systems, Fuel Cell and Electrolyzer, Simulink Modeling

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1. Introduction

1.1 Background and Motivation

The global energy sector is rapidly shifting toward cleaner and more sustainable power system. In response to the increasing concerns of climate change, greenhouse gas emissions, ecological disgrace, and long-term reduction of non-renewable energy. To decarbonize the electricity sector and meet global carbon neutrality goals, governments, industries, and international organizations have stepped up their efforts to speed up the utilization of renewable source technologies. Solar PV and wind energy systems have seen the fastest growth among the range of renewable energy technologies due to their environmental sustainability, technological maturity, and decreasing installation costs. As renewable energy capacity continues to grow, the world is making strides toward more environmentally friendly and durable energy systems.

However, the widespread adoption of renewables in electrical power systems presents many operational and technical challenges. Renewable energy sources are weather and environment-sensitive and are very dependent on weather conditions and environmental variability when compared to conventional thermal power plants. The generation of solar energy depends on the solar irradiance, cloud cover and seasonal variations, and wind energy generation is greatly affected by the variability of wind speed and atmospheric conditions. This means that renewable electricity generation is always on-off and unpredictable, resulting in the constant variation of electricity generation. The variations pose significant difficulties for the stability, frequency control, voltage control and supply-demand balance of modern power systems.

The intermittency of green electricity generation is one of the key challenges for highly renewable electricity systems, which is a characteristic of renewable energy generation. Egeland-Eriksen et al. (2021) noted that as renewable energy becomes more prevalent, the demand for advanced energy storage and grid balancing technologies grows, since renewable energy sources are not always reliable and continuous. Likewise, Yang et al. (2022) suggested that future electricity transition pathways need to be significantly more flexible and adaptable to the operation of the grid to integrate significant amounts of VRE into the system without compromising electricity reliability and supply security. If not balanced properly, renewable intermittency can lead to voltage instability, frequency fluctuations, renewable energy curtailment, transmission congestion, and lower overall grid reliability.

The operational challenges have led to a need for energy storage solutions that are efficient, large-scale, and can support the integration of renewables and ensure grid stability during periods of variable generation. Traditional battery energy storage systems have been extensively used for short-term power storage like frequency regulation, voltage stabilization, and peak shaving. But batteries are still limited in terms of their discharge time, storage time, degradation after repeated charge-discharge cycles, thermal management, and replacement costs when being used on a large scale. As renewables become more noticeable in global energy systems, the shortcomings of traditional battery storage technologies have driven the need for alternative storage solutions that address long-duration and temporary energy storage.

In this context, hydrogen energy storage has become one of the most favorable long-term energy storage technologies for future renewable-integrated power systems. Hydrogen has several unique properties that set it apart from traditional energy storage methods, such as high gravimetric energy intensity, long duration of storage, fuel flexibility, and cross-sector compatibility. Renewable electricity can be used to split water into hydrogen and oxygen, and the hydrogen can be used for power generation, industry, transport, and heating. The hydrogen can be stored for extended periods of time and even from season to season due to the small amount of self-discharge, thus making it a good choice for long-term energy balancing in renewable energy systems. This storage capability allows to store electricity that is produced by PV at night when electricity demand is low then use it during the day when the electricity demand is high, which increases the use of PV and decreases energy curtailment.

Hydrogen is promising as a key energy exporter in future decarbonized power systems and smart grid infrastructure. Sikiru et al. (2024) emphasized the significant prospective for hydrogen to boost the utilization of green energy, increase the capacity of enduring power storage, and contribute to grid net-zero transition in various areas. The study also revealed that hydrogen can effectively store and transport energy over long distances via pipelines and storage tanks, offering greater flexibility and resilience to future energy systems. Likewise, Maka et al. (2025) explained that green hydrogen technologies have the potential to improve renewable energy reliability while supporting global sustainability goals and carbon reduction efforts.

Hydrogen is not just a storage medium for smart grids; it plays a crucial role in their future. Hydrogen technologies enable the integration of electricity systems with transportation, industrial production, residential heating, and natural gas systems, resulting in multi-energy systems with greater operational flexibility and resilience. Hydrogen energy storage systems can be used to store electricity for long periods of time when electricity generation is high, and then convert the electricity back to hydrogen by electrolyzing it, and then convert the hydrogen back to electricity when load demand is high or renewable power production is low, in the context of a smart grid. This capability allows hydrogen systems to operate as flexible balancing resources, helping to smooth out renewable energy peaks and valleys and maintain grid stability.

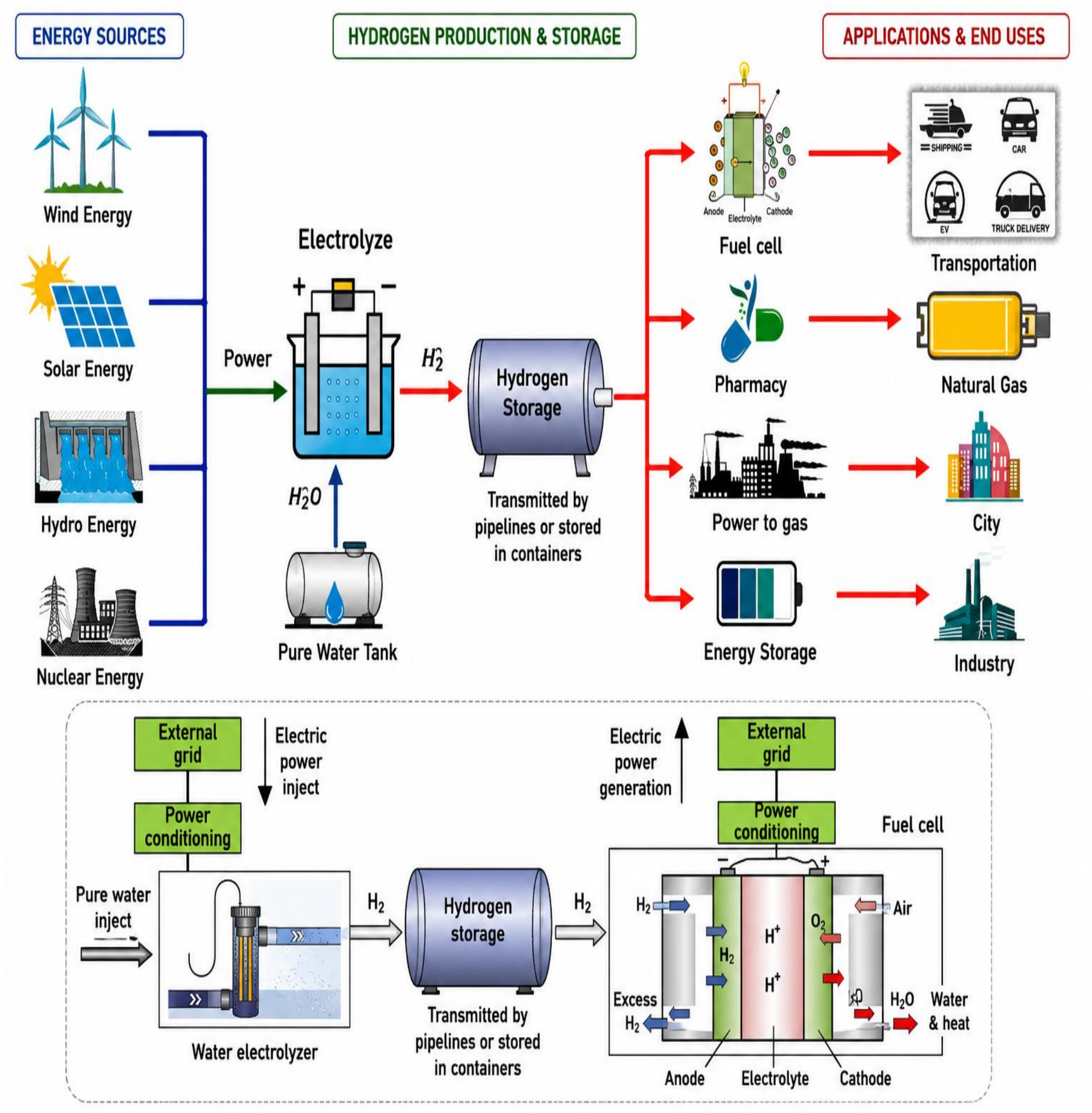


Figure 1. A Grid-Integrated Hydrogen Energy System for Renewable Energy Smoothing

The proposed system architecture typically consists of renewable energy generation systems, electrolyzers, hydrogen storage reservoir, fuel cells, power conditioning systems, and grid integration elements. The clean energy electricity from wind, solar, hydro or other renewable sources is fed into the electrolyzers where the water electrolysis process transforms the electricity into hydrogen. The hydrogen generated is compressed and stored in pressurized storage tanks or piped as required. Stored hydrogen is utilized to regenerate electricity and maintain the grid under conditions of low renewable generation and high power consumption, when electricity is required. The integrated operation structure emphasizes the raising importance of hydrogen as a supply of energy and strategic storage medium in future smart grid architectures. Hydrogen production by electrolysis is a well-studied equipment that combined with renewable energy systems and is environmentally friendly. Electrolyzers can be used in a dynamic way with variable renewable generation by using the excess electricity that is curtailed. In recent years, the technology of alkaline water electrolyzers has been developed and improved in many aspects, in terms of operational efficiency, durability, and hydrogen production capacity. Wang et al. showed that optimized electrode structures and electrochemical configurations can significantly enhance long-term viability and sustainable operation of electrolysers at high current levels. In renewable-integrated grid systems, scientific developments are required to enable production of hydrogen on a large scale and at a reasonable price. Recent studies show that hydrogen-based sustainable energy systems can be beneficial for grid stabilization and smoothing renewables. Wen et al. (2020) studied the hybrid energy storage system of hydrogen and batteries for variable grid connection of wind energy stations, and concluded that the coordinated operational control strategies can effectively enhance the performance of power fluctuation smoothing and reduce the energy loss. Likewise, Elmasry et al. (2024) designed an electricity-hydrogen nexus system using solar photovoltaic generation and multi-level hydrogen storage, and concluded that optimized hydrogen production scheduling minimized the operational costs, increased the utilization of renewable energy, and system flexibility. The results presented here show that hydrogen energy storage can offer significant technical and economic advantages when integrated in green-dominated power techniques. However, even though considerable advances have been made in hydrogen-integrated clean energy systems, several technical and operational challenges still remain unresolved. A key challenge is the low round-trip efficiency of hydrogen energy conversion processes. The electrolysis, compression, storage, and fuel cell reconversion of hydrogen to electricity result in several losses of energy, resulting in a lower overall system efficiency. In the current hydrogen energy storage systems, Egeland-Eriksen et al. (2021) discovered that the efficiency of the hydrogen conversion cycle varies from 60 to 85% of the electrical energy supplied into the system. Additionally to efficiency limitations, the optimization of integrated energy storage systems in highly dynamic operation of renewables is not well explored. The existing literature mostly focuses on simplified simulation scenarios, techno-economic analysis, or optimization of individual subsystems, without taking into account the forecasting of alternative energy generation, the scheduling of the electrolyzer, the management of hydrogen storage, the operation of the fuel cell, as well as the control of the interaction with the grid in a comprehensive optimization framework. According to Irham et al. (2024), the bulk of hydrogen-grid integrating research continues to be based on simulation and does not consider the operational issues of large-scale green energy systems.

Thus, there is a significant need for enhanced modeling and optimization tools to optimize the operational coordination between renewable generation systems, electrolyzers, hydrogen storage, fuel cells and external electrical networks. These optimization methods are vital to better smooth renewable energy generation, limit power fluctuations, lower operating costs, better utilize renewable energy and to support future smart grid development on low-carbon, sustainable and resilient energy systems.

1.2 Problem Statement

Growing interest in sustainable power systems has increased the adoption of photovoltaic and wind power within contemporary electrical networks. Renewable energy technologies are critical to lowering greenhouse gas emissions and promoting sustainable development, but their power generation is also very intermittent and unpredictable because of the variability of environmental and weather conditions. The photovoltaic power generation relies on the sunlight, temperature and the movement of clouds, and the wind energy generation is continuously changing with wind speed and atmospheric conditions. Renewable energy sources cannot be phased out, leading to supply-demand imbalances (Wang and Samuelsen, 2024). The fluctuations pose significant challenges to operations, such as voltage instability, frequency deviation, renewable energy curtailment, power quality, and grid reliability issues. While battery energy storage systems are widely employed for short-term balancing applications, they are not suitable for long-term storage due to degradation, short discharge length, and high operating costs. Khosravani et al. (2026) noted that LDESS are crucial for mitigating renewable energy intermittency and enhancing the technical viability of highly renewable electric power systems.

Hydrogen energy storage is a promising technology that uses additional electricity from renewable sources for electrolysis to make hydrogen. This hydrogen can be stored for extended periods of time and then used to generate electricity via fuel cells when the renewable supply is low. Sustainable hydrogen systems can be used to produce zero-carbon hydrogen for energy generation, transport and industry, as well as to integrate renewable energy (Wang & Samuelsen, 2024). The deployment and use of hydrogen energy storage systems in renewable energy integrated grids, however, are still very complex. Previous research works are mostly based on the analysis of individual subsystems rather than a holistic optimization approach that takes into account the variability of renewable sources, hydrogen production, storage dynamics, fuel cell operation, DC bus stability and grid interaction. Wen et al. (2020) highlighted the need for advanced operational control and optimization strategies to enhance the smoothing performance of renewable energy and the efficiency of the energy system in hydrogen energy systems.

Moreover, Hydrogen systems are still inefficient overall, and suffer energy losses during operation, and have high infrastructure costs (Egeland-Eriksen et al., 2021). Hence, a comprehensive model and optimization framework for grid-integrated HES systems that can optimize the utilization of renewable energy, minimize fluctuations of renewable power, and enhance overall grid stability under dynamic operating conditions is still needed.

1.3 Aim of the Thesis

The purpose of this analysis is to model and optimize a grid-integrated hydrogen storage of energy to minimize the need for renewable energy interruptions, minimize PV power fluctuations and enhance grid stability during dynamic operating conditions. This allows for the production and storage of hydrogen for future use, which can help to reduce power outages and promote renewable energy.

If solar power production is greater than the load demand, the surplus is fed into an electrolyser via a controlled DC bus system. Water electrolysis is used to make hydrogen. After production, the hydrogen is transferred to a storage tank for subsequent applications, thereby enhancing the use of renewable energy and minimizing power curtailment.

If the grid requires more electricity than the PV system can generate, stored hydrogen is pumped into the fuel cell system to produce electricity. The proposed hydrogen energy storage system is designed to be a long-duration balancing resource that can help mitigate fluctuations in renewable energy sources and improve grid reliability by coordinating energy conversion and storage. Hence, this study also seeks to improve the operational coordination of solar generation, electrolyzer scheduling, hydrogen storage management, the fuel cell and grid interaction, which increases the suppleness and consistency of smart grids, enhances the practice of renewable power, minimizes energy losses, and increases the productivity of hydrogen storage.

1.4 Objectives

1.4.1 Develop mathematical models of the components

This study aims to build mathematical models for the key components of the proposed grid-integrated hydrogen energy storage system and to base system-level optimization on these models. The electrolyser, hydrogen storage tank, and fuel cell will be the most important units that will convert and store energy in the hydrogen system. The importance of properly modelling the physical and operational characteristics of the electrolyser and fuel cell in dynamic environments has been highlighted in previous studies for hydrogen system modelling. The model will mimic water electrolysis to generate hydrogen using excess PV electricity for the electrolyser. The electrochemical reactions can be represented as:

$$H2O \rightarrow 2H + +\frac{1}{2}O2 + 2e \qquad (1)$$

$$2H^{+} + 2e^{-} \rightarrow H_2 \qquad (2)$$

The hydrogen production can be written as: 2 moles of electrons are needed to produce 1 mole of hydrogen, so the equation can be written using Faraday's law as:

$$nH2 = \frac{Qe}{2F} \qquad (3)$$

The volume of hydrogen production (nH2) is proportional to the electric charge (Qe) and the Faraday constant (F). The mass flow rate of hydrogen from an electrolyser is given by the product of the electric charge, the current, and the time:

$$\{m\}_{\{H_2,EZ\}} = \left\{I_{\{EZ\}\eta_{\{FM\}M_2}}\right\}\{2F\} \qquad (4)$$

where $I_{EZ}$is the electrolyzer current, $\eta_F$is the Faraday efficiency, and $M_{H_2}$is the molecular weight of hydrogen. This formulation follows the electrochemical modeling approach used for hydrogen production and consumption in hydrogen energy storage systems.

The input power to the electrolyzer is proportional to the cell voltage and current of the electrolyzer and can be expressed as:

$$P_{EZ}=V_{cell,EZ}I_{EZ} \qquad (5)$$

The available electrolyzer power can be expressed as: in the renewable-hydrogen configuration, the electrolyzer will be used when PV generation is greater than the grid demand.

$$PEZ = PPV - Pload, PPV > Pload \qquad (6)$$

The voltage of the electrolyzer cell can be modeled by taking into account the reversible voltage and losses due to overpotential:

$$Vcell, EZ = V0 + Vact + Vohm + Vcon \qquad (7)$$

Where (V0) is the reversible cell voltage, (Vact) is the voltage fixed to the cell, (Vohm) is the operational latent, and (Vcon) is the overpotential. Voltage drops caused by activation, concentration, and ohmic overpotentials have a major effect on electrolyzer and fuel cell performance.

The model will simulate the dynamic balance of the hydrogen utilization of the fuel cell and the hydrogen generation of the electrolyzer in the hydrogen reservoir. The bulk of hydrogen deposited can be written as:

$$mH_2,t+1=mH_2,t+mH_2,EZ^{\Delta t}-\dot{m}H_2,FC^{\Delta t} \qquad (8)$$

where $m_{H_2,t}$is the stored hydrogen mass at time t, $\dot{m}_{H_2,EZ}$is the hydrogen generation rate from the electrolyzer, $\dot{m}_{H_2,FC}$is the hydrogen use rate by the fuel cell, and $\Delta t$is the simulation time step. For pressure-based tank modeling, hydrogen density can be expressed as:

$$\mathrm{\rho H2, t + 1 = \rho H2, t + m^{\cdot}H2, EZ} - \frac{\mathrm{m^{\cdot}H2,FC}}{\mathrm{Vtank}} \qquad (9)$$

where $V_{tank}$is the tank volume. A simplified ideal gas relationship may then be used to estimate tank pressure:

$$P_{\{tank,t\}} = \backslash frac\left\{m_{\{H_2,t\}RT_{\{tank\}}}\right\}\left\{M_{\{H_2\}V_{\{tank\}}}\right\} \qquad (10)$$

The gas constant (R), the tank temperature $T_{tank,}$ and the molecular weight of hydrogen m_{H2}. More advanced equations, like the Peng-Robinson equation, can be employed for high pressure storage as it more closely represents the behavior of real gas under high pressure storage conditions for hydrogen.

The model will model the generation of electricity from stored hydrogen in the fuel cell when demand on the grid is greater than PV generation. The output power of the fuel cell can be written as:

$$P_{FC}=V_{cell,FC}I_{FC} \qquad (11)$$

The operating logic proposed is that the fuel cell provides energy when the PV energy is not enough:

$$P_{FC}=P_{load}-P_{PV}, P_{load}>P_{PV} \qquad (12)$$

Alternatively, the rate of hydrogen utilization of fuel cell can be calculated by Faraday's law:

$$\dot{}\{m\}_{\{H_2,FC\}} = \backslash frac\left\{I_{\{FC\}\eta_F M_{\{H_2\}}}\right\}\{2F\} \qquad (13)$$

The fuel cell voltage is the reversible voltage minus the significant voltage losses:

$$V_{cell,FC}=V_0-V_{act}-V_{ohm}-V_{con} \tag{14}$$

Activation, concentration, and ohmic losses negatively affect the voltage generated by the fuel cell in the hydrogen-to-electricity process. Thus, the mathematical modelling goal in this study is to develop and combine these equations of the electrolyzer, hydrogen storage tank, and fuel cell within a single framework of grid-connected hydrogen energy storage. These models will enable the system to simulate hydrogen production when PV generation is abundant, the hydrogen storage response over time, and generation from the fuel cells when the renewable energy supply is insufficient. The integrated model will then serve as the foundation for optimizing renewable energy use, minimizing power fluctuations, and enhancing grid stability.

1.4.2. Modelling of Renewable Energy Sources

The goal of this research is to create mathematical models of renewable energy resources that are incorporated into the proposed hydrogen energy storing system, namely solar photovoltaic and wind energy systems. The solar photovoltaic model will be used to model the relationship between solar irradiance, temperature, and electrical power generation. The output power of the photovoltaics is given by:

$$P_{PV}=\eta_{PV}A_{PV}G_t \tag{15}$$

where P_{PV} is the photovoltaic power, is the photovoltaic efficiency, A_{PV} is the photovoltaic panel area, and G_t is the solar irradiance. The wind energy model will describe the conversion of wind kinetic energy into electric power. The wind turbine output power can be represented as:

$$P_{WT}=\frac{1}{2}\rho ACpV^{-3} \tag{16}$$

where P_{WT} is the wind turbine energy output, ρ is the air density, A is the rotational area of the wind turbine blades, C_p is the power coefficient, and V is the wind speed. These renewable energy models will be integrated into the overall system to evaluate renewable power fluctuations and energy availability under varying environmental conditions

1.4.3 Modeling of DC Bus and Grid Interface

Another goal of the study is to model the DC bus and grid interface that will control the power flow between the renewable energy sources, electrolyzer, fuel cell, hydrogen storage, and the electrical grid. The balance of generated power, consumed power and stored energy in the system will be represented by the DC bus model. The power balance equation of the DC bus is given by

$$P_{PV}+P_{WT}+P_{FC}=P_{Load}+P_{EZ}+P_{Grid} \qquad (17)$$

where P_{PV} and P_{WT} are the renewable power outputs, P_{FC} is the fuel cell power, P_{Load} is the load demand, P_{EZ} is the electrolyzer power consumption, and P_{Grid} is the power exchanged with the grid. This model will support the analysis of power coordination and stable grid interaction under dynamic operating conditions.

1.4.4. Development of Energy Management Strategy

The other goal of this study is to design an energy management plan to control the power distribution in the grid-integrated hydrogen-based storage system. The proposed method will determine the working parameters of the electrolyze, fuel cell, and hydrogen storage tank, depending on the grid demand and availability of renewable energy. The electrolyze will be used to create and store hydrogen if the amount of renewable electricity generated exceeds the load requirement. Conversely, when the renewable energy supply is not enough, the fuel cell will convert the stored hydrogen into electricity and meet the grid demand. This operational strategy will enable the efficient use of energy, stable operation of the system, and enhanced energy smoothing from renewables.

1.4.5. Optimization of System Performance

Optimizing the execution of the suggested energy storage system in terms of efficiency, operating costs, hydrogen utilization, and grid stability is the ultimate goal of this research. The optimization approach will focus on reducing losses and operating costs in the system and increasing the consumption. The energy conversion efficiency of the fuel cell, hydrogen storage system, and electrolyzer will be used to assess the system efficiency. The efficiency of hydrogen utilization will be investigated to confirm the generation, storage, and utilization of hydrogen under different operating conditions. Moreover, the potential of the proposed system to reduce the flexibility of renewable energy and to confirm a stable energy supply to the electrical grid will be evaluated.

1.4.6. System Validation with MATLAB/Simulink

The proposed grid-integrated hydrogen energy storage system will be validated in the Simscape Electrical environment. The Simulink model is designed to simulate the dynamic behavior of the entire system under different renewable generation and load scenarios, including the PV system, DC bus, electrolyzer, hydrogen storage tank, fuel cell, DC/DC converters, load demand, and grid interface.

The simulation model provides the excess photovoltaic power to the electrolyzer for hydrogen production and storage when the generation demand is greater than the capacity demand. On the other hand, if the load demand is greater than the PV generation, the When needed, the fuel cell will burn the stored hydrogen to produce electricity. The simulation results will be used to assess the performance of the renewable energy smoothing, hydrogen production and consumption behaviors, DC bus stability and the performance of the proposed energy management and optimization strategy.

2. Literature Review

2.1 Renewable Energy Systems and Grid Integration

The global shift towards low-emission and sustainable energy systems is driving the growth of solar PV and wind energy installations. Many nations have been motivated to include renewable energy as a major component of their future electricity generation systems due to growing environmental concerns, CO2 gas emissions, and the depletion of fossil resources. Sustainable energy machinery is also seen as environmentally friendly, as they produce electricity with low carbon emissions and less reliance on traditional power generation methods. Renewable energy systems are key to global decarbonization goals and sustainable development targets, as they offer more sustainable alternatives to traditional energy sources, explained Maka et al. (2025).

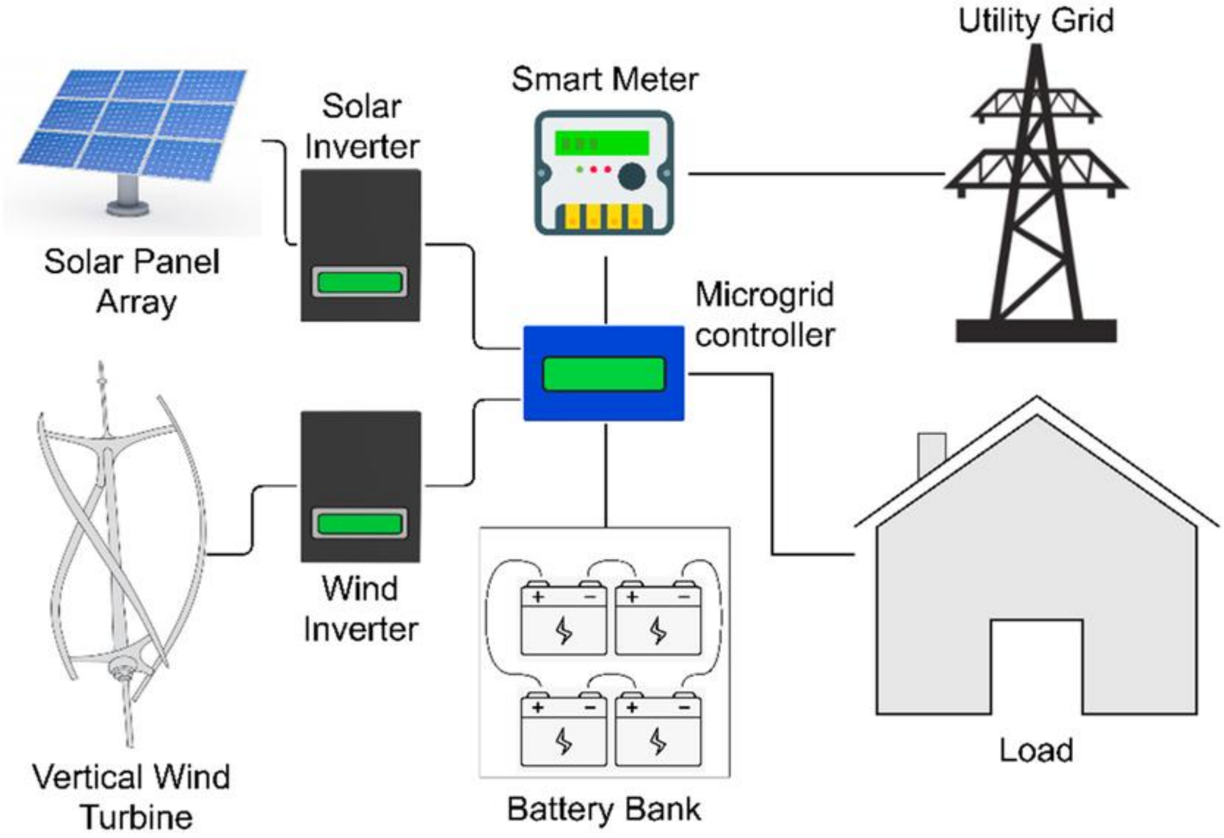


Figure 2.Renewable Energy Systems and Grid Integration

Solar PV systems are systems that use semiconductor materials to directly transform solar irradiance into electricity. Solar PV technology has emerged as one of the renewable energy sources with the quickest growth technologies globally as manufacturing costs have fallen, efficiency has improved and it has been widely deployed. Solar systems are commonly used in households, factories, shopping malls, and large-scale energy applications.. PV power generation, however, is highly dependent on solar irradiance and the environment and the power generation fluctuates considerably during the day. Solar power generation is directly affected by cloud movement, seasonal variation and temperature changes, which introduce variability into the electrical grid.

The rotational motion created by wind is utilized by turbines to generate electrical energy. Because of the technologies and cost reduction of installation, the use of wind power systems has increased very rapidly globally. Wind power is now being increasingly integrated into large power systems and microgrids. However, the variability of wind speeds results in intermittent power generation, which can cause unstable operation of the grid when the share of renewables is high. Wang and Samuelsen (2024) mentioned that integrating large amounts of renewable energy poses effective obstacles because green power generation is not fully dispatchable and does not align with the load demand profile.

Incorporating renewable energy technologies into contemporary electrical networks poses multiple technical challenges, such as power quality, voltage control, frequency regulation, and balancing supply and demand. Renewable intermittency can lead to frequent fluctuations in electricity generation, leading to instability in the transmission and distribution network. The conventional power systems were not originally designed for variable renewable energy systems, which are not controllable or centralized. Thus, to ensure the power quality enhancement of modern smart grids in high renewable penetration scenarios, advanced energy management systems, flexible control strategies, and efficient energy storage technologies are needed.

Microgrid systems can control energy generation, energy storage, demand, and interconnection with the utility grid at the local level, establishing them as a practical solution for renewable energy deployment. Figure 2.1 shows a typical microgrid system that integrates PV arrays and wind turbines, along with battery storage systems, smart meters, and a microgrid controller that communicates with the utility grid. To guarantee dependable and stable operation, the flow of electricity between generation units, energy storage devices, and demand is regulated by the microgrid controller. These technologies help to decrease reliance on traditional methods of power generation and promote the adoption of sustainable energy sources.

Hydrogen energy storage is being seen as a key technology to provide solutions to sustainable energy integration challenges. Egeland-Eriksen et al. (2021) highlighted the need for energy storage technologies to enable the integration of VRES and enhance grid reliability. Likewise, Hydrogen storage help integrate renewables by storing surplus renewable electricity when generation is high and providing electricity when renewable generation is low (Zhang 2024). Hence, Smart grid networks will need to integrate renewable generation and energy storage solutions in a coordinated way in the future.

2.2 Modern Energy Storage Solutions

Modern Energy Storage Solutions are crucial for renewable energy systems, as they enhance energy flexibility, balance power supply and demand, and mitigate the impacts of renewable intermittency. The advantages of operation vary according to storage duration, response time, energy density, efficiency, scalability and cost, for different storage technologies. Therefore, choosing the right energy storage technology is crucial for stable and reliable power systems that integrate green energy.

Battery storage systems are gaining popularity as energy storage solutions due to their efficient performance and compatibility with electrical networks. Renewable smoothing, frequency regulation and short duration storage applications are typical uses of lithium-ion batteries. Batteries can quickly adjust to sudden changes in power, and they can play a role in stabilizing the grid during transient periods. Battery systems, however, have several drawbacks such as high capital cost, limited lifetime, degradation after repeated charging cycles, thermal management issues, and decreased suitability for long duration storage applications. Wang and Samuelsen (2024) pointed out that battery systems are very good for temporary energy storage, they are not economically viable for seasonal or large-scale storage.

Another energy storage technology with very high power density and response time is supercapacitors. Supercapacitors can be used in applications where quick energy delivery and short-term power compensation is required. They are commonly employed in voltage stabilization, transient smoothing, and power quality enhancement. Supercapacitors, however, have low energy density, meaning that they cannot store as much energy for as long. As a result, they are typically used for short-term support and not for large-scale renewable energy balancing.

One of the highly promising sustained energy storage technologies for upcoming energy systems that incorporate green energy sources is hydrogen energy storage. In the storage, excess green power is electrolyzed to convert energy into hydrogen, then preserved for long-term use of time before being utilized by fuel cells to generate electricity.

Hydrogen has potential applications in several fields, including power production, transport systems, industrial activities, and chemical synthesis. Maka et al. (2025) described green hydrogen as a means of long-term storage of renewable energy, as well as a tool for decarbonization in various economic sectors.

However, hydrogen systems are typically not as efficient as batteries because of losses during hydrogen production, hydrogen compression, storage, and fuel cell conversion processes. However, hydrogen systems have much greater storage capacity and storage time than traditional battery systems. Khosravani et al. (2026) showed that hydrogen and battery storage solutions can improve the penetration of renewables and reduce operating costs, with hydrogen providing long-duration storage and batteries providing fast response. Thus, hydrogen systems are seen more as complementary technologies to battery systems, and not as competitors.

In recent years, other advanced hydrogen storage technologies have been explored, such as underground hydrogen storage, metal hydrides, ammonia-based hydrogen carriers, and solid-state hydrogen storage systems. Researchers are exploring materials like magnesium hydrides, high-entropy alloys, and metal-organic frameworks for their potential to store more hydrogen in a safer way. There are still, however, a number of these technologies that are still in development and have commercialization barriers of cost, material stability, and large-scale deployment.

Table 1. Comparison of storage systems

Technology	**Advantages**	**Limitations**
Batteries	High efficiency, fast response, mature technology, suitable for short- to medium-duration storage	Limited lifetime, degradation over cycling, safety and thermal-management concern
Supercapacitors	Rapid response, high power density, and long cycle life	Low storage capacity, which restricts its use in long-duration applications
Hydrogen storage	Suitable for long-duration and seasonal storage, scalable for large energy capacity	Lower round-trip efficiency, added conversion losses, higher system complexity

Due to cycle degradation, limited lifetime and replacement cost, the application of battery storage is primarily considered for short and medium-term balancing. Hydrogen storage, on the other hand, has lower round-trip efficiency because of the losses in electrolysis, compression, storage, and fuel cell reconversion, but offers better long-duration storage potential and increased scalability for renewable-dominated electricity systems. Thus, batteries are better suited for fast response applications, and hydrogen storage is better suited for smoothing and balancing long-duration renewables and seasonal energy. This study is a step forward from the existing literature by considering the coordinated operation of the PV generation, electrolyzer scheduling, hydrogen storage management, fuel cell dispatch, and DC bus voltage regulation in a single Simulink platform.

2.3 Hydrogen Energy Storage System

Hydrogen storage systems consist of various components that are linked together to allow the production and storage of hydrogen for subsequent electricity generation. The main components include the fuel cell, hydrogen storage tank, and electrolyzer. These components allow the alteration of electrical to chemical, and, if needed, the conversion of stored hydrogen back to electrical energy.

By electrolyzing water, the electrolyzer will create hydrogen. In electrolysis, electricity is applied to water to generate hydrogen and oxygen. The main electrolysis methods consist of alkaline, PEM, solid oxide, and anion exchange membrane electrolyzer systems. Alkaline electrolyzers are widely used due to their relatively low cost and high level of technological development. PEM electrolyzers are costly due to the use of expensive catalyst materials, but can operate at high current density and have a rapid dynamic response.

Ashraf et al. (2025) compared the various electrolyzer technologies and emphasized that the performance of the electrolyzer plays an important part in the efficiency of hydrogen produce, the deployment of sustainable sources, and the economics of the overall system. In a similar manner, Chen et al. (2026) observed that the energy demand associated with oxygen evolution reaction is high in conventional electrolysis systems, and they proposed a decoupled electrochemical approach to optimize hydrogen production performance. The findings also showed that alternative anodic reactions and NiOOH-based catalytic systems can enhance the performance of hydrogen generation and minimize the loss of energy in electrolysis.

The generated hydrogen is kept in storage facilities for later utilization. Hydrogen can be stored in complex materials in the solid, as frozen liquid, or gas. Hydrogen is most commonly stored using compressed gas storage methods; it is both commercially available and technically straightforward. But high-pressure storage systems need robust containment and sophisticated safety systems. Magnesium hydrides and high-entropy alloys are studied as solid-state storage materials to enhance the storage density and safety performance. Furthermore, recent studies explore the feasibility of hydrogen transport by ammonia and hydrogen storage in the ground for large-scale and seasonal storage.

Fuel cells generate electrical power by electrochemical reactions of deposited gas. Hydrogen generates heat, water, and electricity. The advantages of PEMFCs include efficient energy conversion, quick response, and reduced temperature operation. The most popular choice. Fuel cell systems can be especially beneficial in renewable energy systems where renewables are scarce, as they can deliver dispatchable electricity.

The hydrogen energy storage systems rely on efficiency of the electrolyzer, losses in the storage, hydrogen compression, and efficiency of the fuel cell. While the overall round-trip efficiency is still lower than that of a battery system, hydrogen technologies offer benefits in long-duration storage, large-scale energy balancing, and sector coupling applications. Zhang(2024) highlighted the future prospects of hydrogen systems to enable the integration of renewables, the electrification of transportation, decarbonizing industry, and smart grid operation.

2.4 Integration of hydrogen in grid systems

The integration of hydrogen into electrical grids has grown in significance due to hydrogen systems' ability to enhance the efficient use of renewable energy and power system elasticity. Sustainable sources often produce excess electricity at times of low demand or when the environment is conducive to their production. This surplus renewable energy could otherwise be curtailed, impacting system efficiency and economic performance without storage systems. Hydrogen energy storage can support the storage of unused renewable energy as chemical energy then convert it back to electricity when renewable energy is not being generated.

Renewable energy smoothing is one of the key applications for hydrogen integration. Renewable smoothing is the process of smoothing out the variability of renewable energy at a shorter timescale before it is fed into the grid. In hydrogen-integrated systems, renewable electricity is used to produce hydrogen, instead of being curtailed. In times of renewable power shortages, the fuel cell converts stored hydrogen into electrical power to smooth out power production. Wen et al. (2020) showed that the hydrogen-battery hybrid energy storage system not only reduces the fluctuation of energy but also enhances the performance of grid connection.

Also, hydrogen systems can be used for load levelling and peak shaving. Load levelling helps to smooth out electricity use over time and peak shaving helps to lower electric demand during peak hours. Hydrogen can be produced and stored when power is produced in excess or during times of substantial renewable generation. Fuel cells can produce energy from stored hydrogen, helping to relieve the pressure on the electrical system during high consumption. Irham et al. (2024) noted that coordinated operation between green energy sources and hydrogen storage can enhance grid flexibility and minimize renewable energy curtailment in hydrogen-integrated systems.

Smart energy management systems, optimization algorithms, and predictive control strategies are becoming more common in modern hydrogen-integrated grids, enhancing their operational efficiency. There are many control strategies being studied for renewable-hydrogen systems, including model predictive control, particle swarm optimization, and artificial intelligence-based control strategies. These techniques can be used to optimize the scheduling of the electrolyzer, dispatching of the fuel cells, the use of hydrogen and the power flow management. Hydrogen systems are relatively less efficient and expensive to operate, which is why advanced energy management strategies are especially crucial.

Hydrogen integration also enables the coupling of electricity, transportation, industrial systems, and chemical production. Hydrogen produced from renewables has applications in transportation apart from electricity production, ammonia production, industrial heating, and chemical processing. This means that hydrogen integration offers more flexibility in the energy system than many traditional storage solutions.

2.5 Mathematical Modeling Approaches

The mathematical modeling is crucial to understanding the operating behavior of systems that incorporate hydrogen and evaluating the system's performance under various operating circumstances. Renewable generation variability, hydrogen production dynamics, storage behavior, operation of fuel cells, power flow management and system optimization are extensively analyzed using mathematical models.

The models of electrolyzer typically explain the correlation between electrical input power, operating current, cell voltage, hydrogen production rate and electrochemical losses. A number of studies rely on Faraday's law to describe hydrogen generation as a function of electrolysis current. More complicated models include activation losses, ohmic losses, concentration losses, thermal effects and dynamic operating conditions. Ashraf et al. (2025) discussed various modeling methods for electrolyzers and noted the significance of the electrochemical modeling of renewable integrated hydrogen systems.

Typical fuel cell models are used to model hydrogen consumption, voltage-current characteristics, efficiency and electrical power generation. Dynamic fuel cell models include activation overpotential, ohmic losses and concentration polarization effects to assess the transient performance under different load conditions. Fuel cell models are particularly significant for the analysis of dispatchable power generation and system response in the case of shortages of renewable energy.

Hydrogen storage models are used to describe hydrogen accumulation, storage pressure change, temperature change, and the supply of hydrogen between electrolyzer and fuel cell. Typical models are simplified and may include mass balance equations, and advanced models can include thermodynamic and real gas behaviour. Different modeling methods are needed for several forms of subsurface hydrogen storage, compressed gas storage and solid-state storage.

Renewable energy models are used to model solar PV and wind energy generation, based on environmental conditions like irradiance, temperature, and wind speed. Irradiance-based current-voltage equations are commonly used in solar PVs, and aerodynamic equations are used in wind turbines that relate wind speed and power output. These renewable models are important for assessing the fluctuating nature of renewables and energy management strategies.

These component-level models have been integrated into renewable-hydrogen system models in several studies. Optimization models for the production of renewable hydrogen with on-grid and off-grid operating conditions were developed by Wan et al. (2024). Wen et al. (2020) proposed hybrid wind-battery-hydrogen model for flexible renewable integration and power smoothing. More recent studies also involve the application of hybrid optimization and physics-informed AI models to improve operational performance and predictive accuracy

Since MATLAB/Simulink can be used for dynamic simulation, integration of control systems, modeling of power electronics, and optimization analysis, it has become one of the most commonly used platforms for modeling renewable-hydrogen systems. Simscape Electrical is ideal for modeling renewable generation systems, DC buses, converters, electrolyzers, fuel cells and grid interaction in a single simulation environment.

2.6 Research Gap

Hydrogen energy storage systems have been the subject of much research but there are some important research gaps that have yet to be addressed. While many of the current studies concentrate on individual subsystems like electrolyzers, fuel cells, renewable generation, or storage technologies, they do not build a fully integrated framework of a renewable-hydrogen grid. Therefore, many studies do not fully consider the interaction between the intermittency of renewables, hydrogen production, storage dynamics, dispatch of fuel cells, stability of the DC bus, and grid operation.

The other significant constraint is related to energy management and optimization strategies. The round-trip efficiency of hydrogen systems is relatively low, and efficient operational coordination is necessary, as in the case of batteries. Suitable control strategies can result in hydrogen losses, lower renewable utilization and higher operational cost. There are a number of studies that suggest optimization algorithms and predictive control methods, but many of the current methods are still too complex or only applicable to simplified operating conditions. Irham et al. (2024) highlighted the need for continued research-based approaches to the sustainability, performance, and optimization of hydrogen-based renewable energy systems.

Moreover, most of the past research has been limited to short-duration renewable fluctuations, while not considering long-duration renewable balancing and seasonal storage needs. Due to storage time constraints and degradation, battery systems are not sufficient for large scale renewable penetration. As a result, the integration of hydrogen systems needs to be improved, so that the combination of generation, production, hydrogen storing and fuel cell operation can be coordinated over various time scales.

Another significant gap is the absence of a common framework for simulations that can integrate renewable energy sources, hydrogen systems, DC bus operation, grid interaction, and optimization strategies in a dynamic modeling environment. Previous research typically does not consider practical operational coordination between renewable energy and hydrogen systems under variable load conditions. This thesis aims to fill these gaps by designing a comprehensive MATLAB/Simulink-based modelling and improvement outline for a grid-integrated hydrogen energy storage system to smooth out renewable energy, optimize hydrogen utilization, stabilize the DC bus, and stabilize the grid under dynamic operating conditions. In this research, an integrated system is designed to overcome the limitations found in previous works to enhance the smoothing of renewable energy and maintaining DC bus stability during different operating modes.

This study is novel in the sense that it integrates the coordination of PV generation, the operation of the electrolyzer, the control of hydrogen storage, the dispatch of the fuel cell, and the control of the DC bus voltage in a single MATLAB/Simulink environment. This work is different from studies that only consider individual components or techno-economic assessment, as it considers the dynamic operational behavior of the entire hydrogen-integrated renewable energy system under varying load and renewable generation conditions.

3. System Description and Architecture

3.1 Overall System Configuration

The integrated framework is a grid-integrated hydrogen energy storage system that is designed to control renewable power variability and stabilize the electrical grid. The overall structure involves a 600KW solar PV system, an electrolyzer, a hydrogen storage tank, a fuel cell, a DC bus, power electronics converters, and a utility grid connection. The renewable energy sources serve as the main energy production units, while the hydrogen energy storage system is designed to act as a long-duration storage and backup power solution, ensuring energy supply stability in the face of fluctuations in renewable energy production.

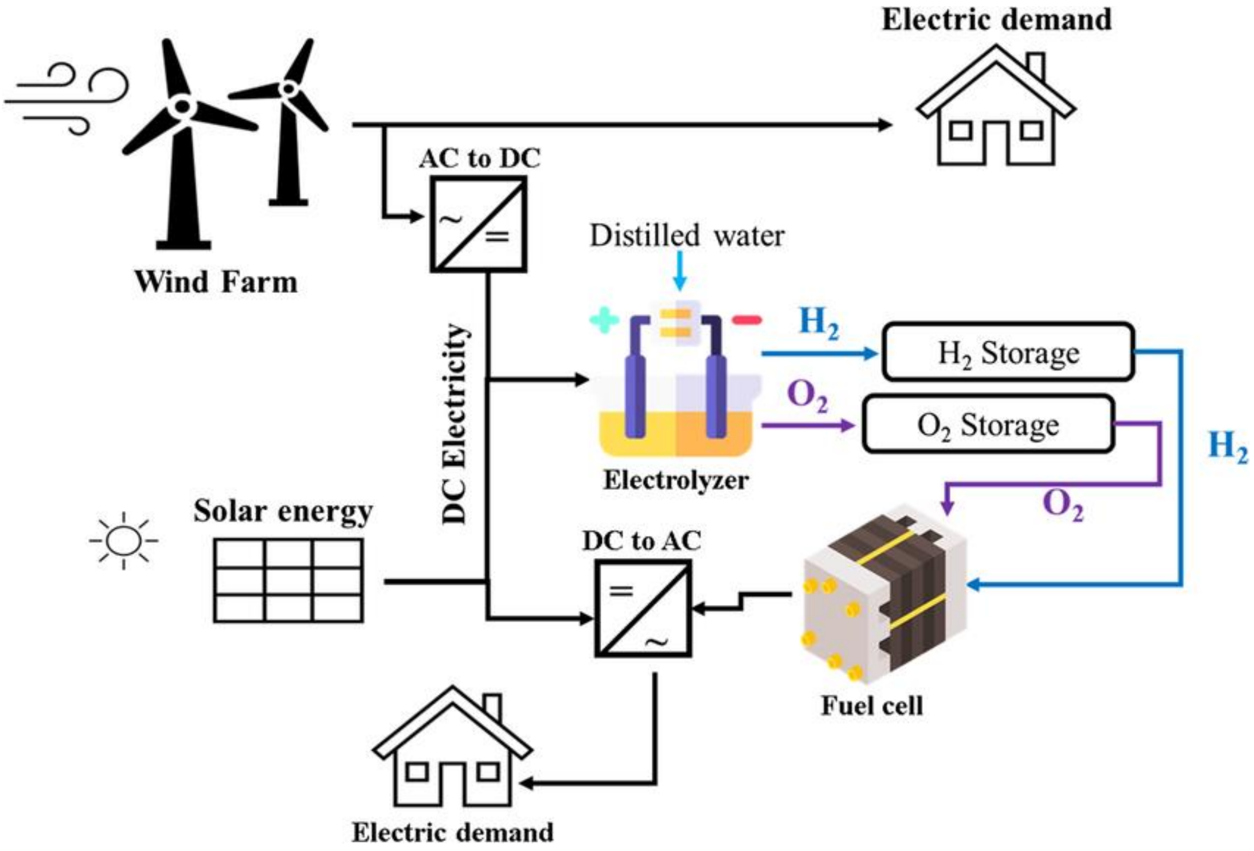


Figure 3. Overall System Diagram

The renewable hydrogen energy storage system configuration is illustrated in Figure 3. The proposed architecture includes inverter and converter systems to convert and regulate electrical power from the solar photovoltaic array and wind turbine to the DC bus. The nominal operating voltage of the DC bus is 500 V and it acts as the main power exchange interface between renewable energy sources, the electrolyzer, the fuel cell, the electrical load, and the utility grid. When renewable generation is available, the renewable generation system provides electricity directly to the load demand. Renewable generation is also intermittent and weather sensitive, however, and extra energy management and storage systems are needed to ensure stable operation.

Solar PV is the primary renewable energy technology used in the proposed configuration. The solar PVs are designed to be 600kW total installed capacity to generate large-scale renewable power under different irradiance conditions. DC/DC converter connects the photovoltaic system to the DC bus while regulating voltage, ensuring maximum power extraction and stable output regulation. The wind energy system is also optional and can link to the DC bus to diversify the power generation and lessen the reliance on solar-only power generation. The wind system generates wind power and provides extra renewable power when the sun is not generating power.

The hydrogen storage framework includes an electrolyzer, hydrogen tank, and fuel cell integrated into a single regenerative energy system. The electrolysis process uses excess renewable energy to split water into hydrogen gas. Distilled water and electrical energy separate particles into hydrogen and oxygen in the electrolyzer. If the renewable energy is not available, the electrolyzer-produced hydrogen is utilized and stored. This energy management method allows the surplus PV power to be transformed into chemical energy and stored for extended periods. When renewable generation is not available, the stored hydrogen can be used to meet load demand and ensure uninterrupted delivery of DC bus power to the load. As a result, the integrated hydrogen storage system boosts the utilization of sustainable sources, reduces generation intermittency, as well as improves the hybrid renewable energy system's dependability. Electrical energy is produced by the fuel cell from hydrogen to supply the DC bus and connected loads. With just one electrochemical cell, a unitized regenerative hydrogen fuel cell system is a condensed kind of regenerative fuel cell. It can produce hydrogen by electrolysis mode electrolyzer (EL mode) and power by fuel cell (FC mode).

With just one electrochemical cell, a regenerative PEM fuel cell system is a condensed kind of regenerative fuel cell. It can produce power in a fuel cell, and it constructs hydrogen in an electrolyzer.

The conceptual schematic of the URPEMFC system can be seen in Figure 4. In the FC mode, the stored hydrogen will return to the cell to generate electricity, while in the EL mode the energy input can be used for the splitting of water for hydrogen production. These reactions can proceed indefinitely when water and electrical power are supplied in electrolyzer mode, and hydrogen and oxygen are supplied in fuel cell mode.

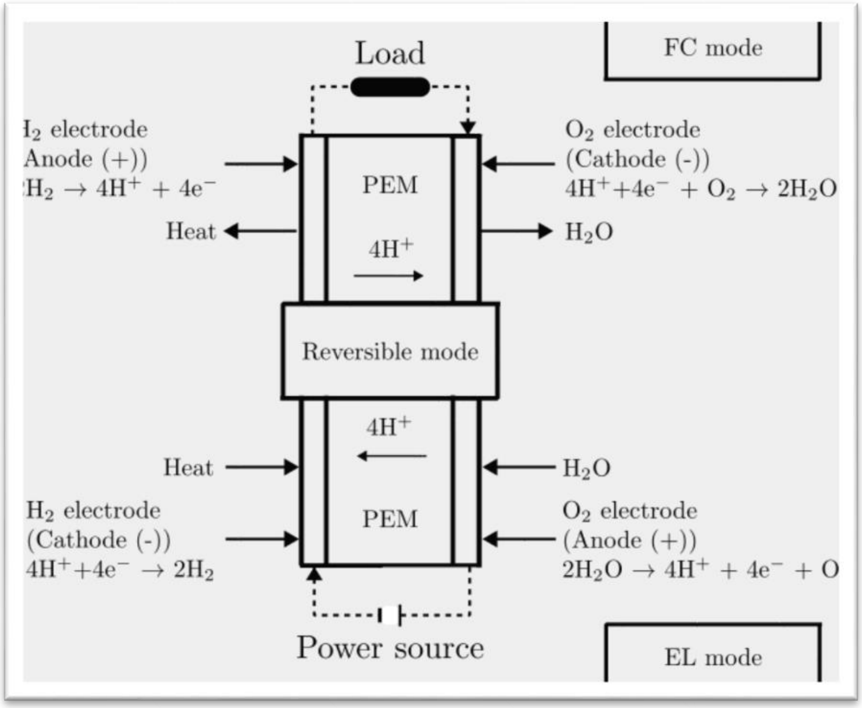


Figure 4. Diagrammatic representation of a URBEMFC system.

Equations (17) and (18) show that the generation of hydrogen in the electrolyzer operation, the energy from electricity is used to separate water into the gases hydrogen and oxygen; in the fuel cell operation, hydrogen reacts with the oxygen to produce water and release energy:

$$2H_{2O_{\{(l)\}}} + \backslash text\{electricity\} + \backslash text\{heat\} \qquad (17)$$

$$2H_{\{2(g)\}} + O_{\{2(g)\}}, \backslash qquad \left(\Delta G^{\{o\}}_{\{EL\}} = +nFE^{\{o\}}\right) \qquad (18)$$

The mass conservation in the cathode and anode, the reaction kinetic, the thermodynamic properties and the voltage ancillary are all factors that must be considered in any model of PEM electrolyzers. Bearing in mind these principles, a general model for describing the states of the system can be developed.

The equations of the developed model will be given in the following sections. The model and operating limits in the systems review are in Table 2. Additionally, the ensuing statements were made in the modelling approach:

The modules were classified as initiation,

1. Electrical resistance and concentration.
2. The system operation follows the principles of thermodynamics and electrochemistry.
3. The model assumes conservation of both mass and energy.
4. Electron crossover through the membrane is assumed absent in both operating modes.
5. A steady-state operating condition is considered.
6. The mole balance at the positive and negative electrodes is preserved.
7. The model considers the gases to be ideal.

Table 2. Design characteristics and operational parameters.

Parameter	Value	Unit
Reversible potential of URPEMFC	1.23	V
Number of cells in the stack	10	cell
Active cell area	100	cm^2
Cell current density (fuel cell, iFC mode)	0.5	A/cm^2
Cell current density (electrolyzer, iEC mode)	0.5	A/cm^2
Mean stack voltage at EL mode	59	V

Mean stack voltage at FC mode	18	V
Mean stack power consumed at EL mode	3090	W
Mean stack power consumed at FC mode	728	W
Temperature (T)	353.15	K
Anode activation constant (αanode)	0.0304	V
Cathode activation constant (αcathode)	0.0507	V
Lost internal current density (iLoss)	0.008	A/cm²
Anode exchange current density (i0,anode)	0.15	A/cm²
Area specific ion resistance (Rion)	0.01	Ω/m²
Area specific contact resistance (RCR)	0.03	Ω/m²
Anode empirical constant (Banode)	0.0152	V
Cathode empirical constant (Bcathode)	0.0152	V
Anode limiting current density (iL,anode)	1.5	A/cm²
Cathode limiting current density (iL,cathode)	2.5	A/cm²

Hydrogen partial pressure (PH_2)	1	atm
Water partial pressure (PH_2O)	1	atm
Oxygen partial pressure (PO_2)	0.21	atm
Gas constant (R)	8.3145	J/mol·K
Faraday's constant (F)	96485	C/mol

3.2 Operating Modes

The EL mode operates with a reversible potential expressed as

$$ENernst, EL = Erev + nFRTlog(\text{PH2OPO2PH2}) + Eact, total + Eohm, total + Econ, total \qquad (19)$$

whereas the reversible potential in the FC mode is

$$E_{\{Nernst,FC\}} = E_{\{rev\}} + \backslash frac\{RT\}\{nF\}\backslash log\left(\backslash frac\left\{P_{\{H_2\}\sqrt{\{P_{\{O_2\}}\}}}\right\}\{P_{\{H_2\}}\}\right) - E_{\{act,total\}} - E_{\{ohm,total\}} - E_{\{con,total\}} \qquad (20)$$

The net activation overpotential of the URPEMFC depends on the activation losses at both electrodes:

$$Eact,total=n\alpha FRT[log(io,anodeiloss+i)+log(io,cathodeiloss+i)] \qquad (21)$$

Protons moving through the polymeric membrane, resistance from particular contacts, and The flow of electricity through conductive components experiences resistance, resulting in ohmic overpotential. The entire ohmic overpotential is the sum of these elements:

$$E_{Ohm,total} = i\left(R_{elect} + R_{ion} + R_{cr}\right) \quad (22)$$

Concentration overpotentials are caused by the system reactants, products and ions not being fully removed. Proton concentration differs on both sides of the polymeric membrane rely on the URPEMFC performing situations. Also the generation of water in fuel cell mode relies on efficient proton exchange between the two electrodes. The overall concentration polarization of the URPEMFC system is calculated as the sum of the electrode concentration:

$$Econc, total = nFRT[log(1 - il, anodei) + log(1 - il, cathodei)]Econc, total = nFRT[log(1 - il, anodei) + log(1 - il, cathodei)] \quad (23)$$

In the electrolyzers, hydrogen production fluctuates with consumption of energy, while Fuel cell, energy production fluctuates with hydrogen utilaization. The following equation express the net balances of hydrogen of a URPEMFC system:

$$pHL_{stac} = \begin{cases} H_{2EL} > H_{2fc}, & \text{if EL mode produces more } H_2 \text{ than consumed by the FC mode,} \\ H_{2EL} = H_{2fc}, & \text{if EL mode produces the exact } H_2 \text{ consumed by the FC mode,} \\ H_{2EL} < H_{2fc}, & \text{if EL mode produces less } H_2 \text{ than consumed by the FC mode.} \end{cases} \quad (24)$$

4: Mathematical Modeling

4.1 Solar PV Model

The proposed grid-connected hydrogen storage configuration is modeled as the main renewable energy source of the PV. The PV system utilised in this study has an array layout of 300 x 8 modules with a total rated capacity of 600kW. The sun irradiation, temperature, output current, output voltage, and electrical power generated are all related by the photovoltaic model. The production current of a PV cell is given by:

$$IPV = Iph - Io[exp(AkTq(VPV + IPVRs)) - 1] - RshVPV + IPVRs \qquad \textit{(25)}$$

I is the output current of the PV module, and I and I are the photocurrent and diode saturation current, respectively. The parameters q, A, k, R, R, and T represent the charge of the electron, the ideality factor of the diode, the Boltzmann constant, the series resistance, the shunt resistance, and the cell temperature.

The output power of the PV array is given by:

$$PPV = VPVIPV \qquad (26)$$

For the total PV array, the generated power may also be represented as:

$$PPV, array = NsNpVPVIPv \qquad (27)$$

here, $N_s$and $N_p$refer to the series and parallel configurations of the PV modules. In this thesis, the PV array is configured using **300 × 8 modules**, and the total rated PV capacity is 600kW.

4.2 Electrolyzer Model

The electrolyzer is a device that converts excess renewable electricity and water into hydrogen by electrolysing them. The modelling of the electrolyzer is done using the principles of electrochemical, thermodynamic and mass conservation. Based on the

URPEMFC modeling assumptions, the voltage losses are divided into activation, ohmic, and concentration overpotentials, and under steady state circumstances, it is expected that mass and energy conservation hold true. The electrolyzer cell voltage can be expressed as:

$$V_{EL} = V_{rev} + V_{act} + V_{ohm} + V_{conc} \qquad (28)$$

For simplified modeling, the main voltage relationship is written as:

$$V_{EL} = V_{rev} + V_{activation} + V_{ohmic} \qquad (29)$$

where V_{EL} is the electrolyzer operating voltage, V_{rev} is the reversible voltage, $V_{activation}$ is the activation overpotential, and V_{ohmic} is the ohmic voltage loss.

The electrical power used by the electrolyzer is:

$$P_{EL} = V_{EL} I_{EL} \qquad (30)$$

The hydrogen production rate is calculated using Faraday's law:

$$\dot{n}_{H_2,EL} = \frac{\eta_F I_{EL}}{2F} \qquad (31)$$

where $\dot{n}_{H_2,EL}$ is the molar hydrogen production rate, η_F is the Faraday efficiency, I_{EL} is the electrolyzer current, and F is Faraday's constant.

The hydrogen mass production rate is:

$$\dot{m}_{H_2,EL} = \frac{\eta_F I_{EL} M_{H_2}}{2F} \text{……………………………} (32)$$

where M_{H_2} is the molar mass of hydrogen.

4.3 Hydrogen Storage Model

If the renewable energy generation is not enough, the hydrogen generated by the electrolyzer is stored in a hydrogen tank and later delivered to the fuel cell. The model of the storage system relies on the mass conservation of hydrogen production and consumption processes.

The hydrogen mass balance is expressed as:

$$\frac{dm_{H_2}}{dt} = \dot{m}_{H_2,EL} - \dot{m}_{H_2,FC} \qquad (33)$$

where $mH2$ is the mass of hydrogen that is stored, $\dot{m}H2,EL$ is the rate at which the electrolyzer produces hydrogen, and $\dot{m}H2,FC$ is the rate at which the fuel cell consumes hydrogen.

In discrete simulation form, the storage equation becomes:

$$m_{H_2}(t + \Delta t) = m_{H_2}(t) + \left(\dot{m}_{H_2,EL} - \dot{m}_{H_2,FC}\right)\Delta t \qquad (34)$$

The hydrogen tank pressure can be estimated using the ideal gas equation:

$$P_{tank} = \frac{m_{H_2} R T_{tank}}{M_{H_2} V_{tank}} \qquad (35)$$

where $P_{tank}$is the hydrogen tank pressure, $R$is the universal gas constant, $T_{tank}$is the tank temperature, and $V_{tank}$is the storage tank volume.

4.4 Fuel Cell Model

The fuel cell produces electrical energy from stored hydrogen whenever renewable power generation is insufficient. In fuel cell mode, stored hydrogen reacts electrochemically with oxygen to generate electrical power, heat, and water. The URPEMFC system can be operated in both electrolyzer and fuel cell modes. In EL mode, hydrogen is produced, whereas in FC mode, it is converted into electrical energy. The voltage of the fuel cell is denoted by:

$$V_{FC} = V_{rev} - V_{act} - V_{ohm} - V_{conc} \qquad (36)$$

where $V_{FC}$is the fuel cell output voltage, $V_{rev}$is the reversible voltage, $V_{act}$is the activation loss, $V_{ohm}$is the ohmic loss, and $V_{conc}$is the concentration loss.

The fuel cell output power is:

$$P_{FC} = V_{FC} I_{FC} \qquad \textit{(37)}$$

The fuel cell hydrogen consumption can be expressed as:

$$\dot{n}_{H_2,FC} = \frac{I_{FC}}{2F} \qquad \textit{(38)}$$

and the hydrogen mass consumption rate is:

$$\dot{m}_{H_2,FC} = \frac{I_{FC} M_{H_2}}{2F} \qquad \textit{(39)}$$

4.5 DC Bus Model

The PV system exchanges electrical power through the DC bus interface, electrolyzer, fuel cell, load and the grid interface. The nominal DC bus voltage used in this study is 500 V. The dynamics of the DC bus voltage are modeled with the capacitor current balance equation:

$$C_{dc} \frac{dV_{dc}}{dt} = I_{in} - I_{out} \qquad (40)$$

where $C_{dc}$is the DC bus capacitance, $V_{dc}$is the DC bus voltage, $I_{in}$is the total input current from the renewable source and fuel cell, and $I_{out}$is the total output current to the load, electrolyzer, and grid interface.

The DC bus power balance can be expressed as:

$$P_{PV} + P_{FC} = P_{Load} + P_{EL} + P_{Grid} \qquad (41)$$

If the amount of renewable power generation is insufficient to meet the load demand, the fuel cell provides extra electrical energy from the stored hydrogen to maintain the operation of the DC bus. This is a dynamic power compensation mechanism that can help maintain voltage regulation and enhance the operational stability of the integrated renewable energy system. When renewable power generation becomes insufficient to meet the energy requirements of the load, the fuel cell supplies additional electrical power using stored hydrogen energy to maintain DC bus voltage regulation. This dynamic power compensation capability enhances voltage stability and supports continuous system operation under fluctuating renewable energy conditions.

4.7 Grid Interface Model

The grid interface controls the flow of power from the designed system to the utility grid. The grid can absorb excess power or generate extra power as per the renewable generation and load demand conditions. The general system power balance is:

$$P_{PV} + P_{Wind} + P_{FC} + P_{Grid} = P_{Load} + P_{EL} \qquad (42)$$

For the proposed PV-based system without wind operation, the equation becomes:

$$P_{PV} + P_{FC} + P_{Grid} = P_{Load} + P_{EL} \qquad (43)$$

During excess renewable generation:

$$P_{PV} > P_{Load} \qquad (44)$$

$$P_{EL} = P_{PV} - P_{Load} \qquad (45)$$

During renewable energy deficit:

$$P_{PV} < P_{Load} \qquad (46)$$

$$P_{FC} = P_{Load} - P_{PV} \qquad (47)$$

Thus, the mathematical model coordinates the 600 kW PV system, 500 V DC bus, electrolyzer, hydrogen storage tank, fuel cell, and grid interface to maintain a stable power balance during variations in energy output and demand load. The developed mathematical models were integrated into a MATLAB/Simulink simulation platform to investigate system efficiency during fluctuating generation and electricity demand.

5 MATLAB/Simulink Implementation

5.1 Simulation Environment

With the aid of the Simscape Electrical environment, the suggested grid-integrated hydrogen energy storage system is constructed in MATLAB/Simulink. A single simulation model is used for the solar PV system, the DC bus, the electrolyser, the hydrogen storage tank, the fuel cell, the load and the grid interface. The solar PV array is linked to the DC bus with a regulated DC-DC converter to ensure a stable energy supply under different operating conditions and maintain the PV array output at the desired value.

The DC bus is the main power exchange node between the hydrogen system, renewable energy source and load demand. If the photovoltaic output is higher than the required load demand, excess energy is directed to the electrolyzer to generate hydrogen. But when PV generation is not enough, the stored hydrogen is fed to the fuel cell to generate energy and power the DC bus. The model also includes voltage, current, hydrogen flow and power monitoring blocks to assess the performance of the system, renewable energy smoothing, hydrogen utilisation, and the dynamic stability performance of the DC bus.

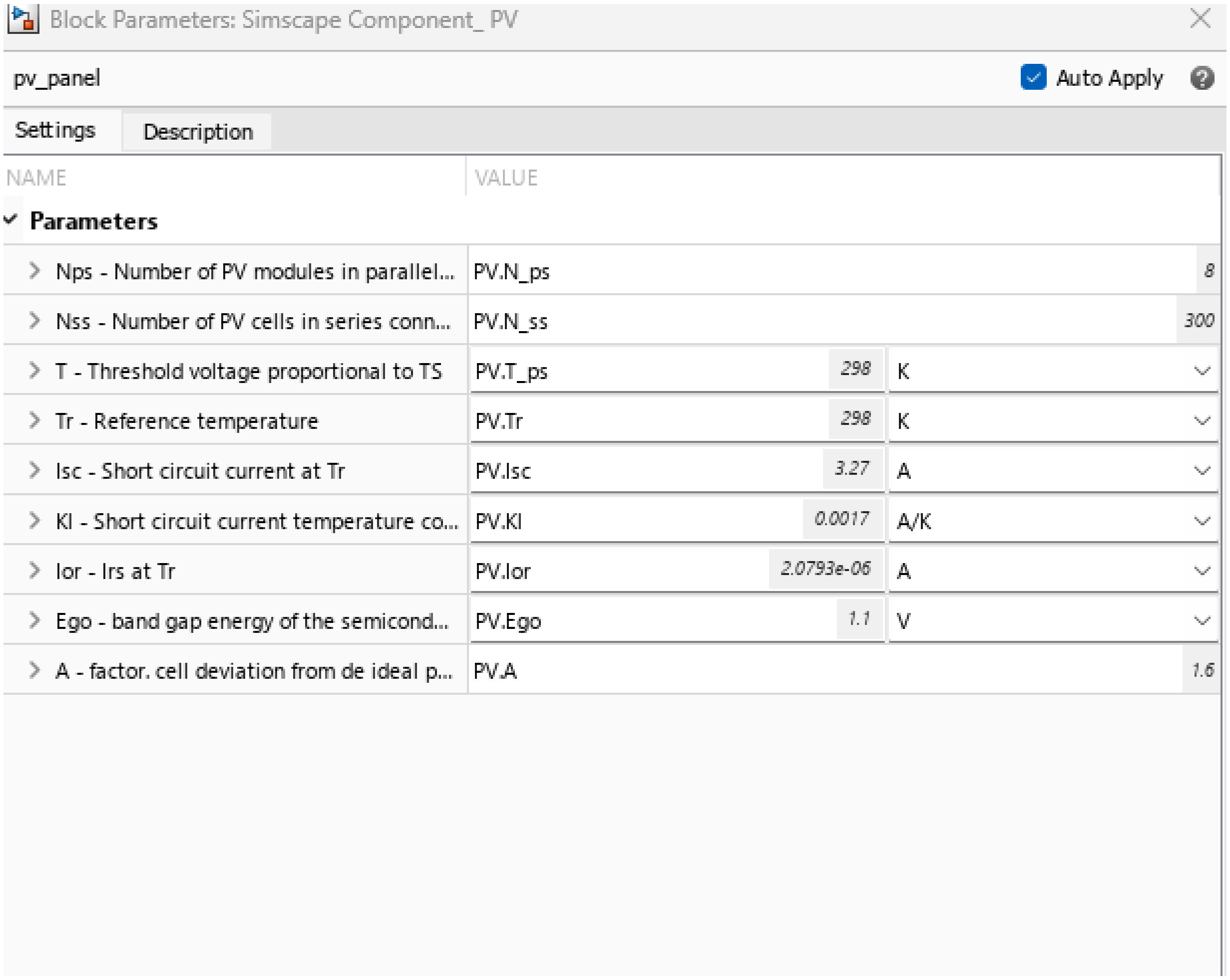
5.2 Component Models

5.2.1 PV system

The solar PV system is developed and analyzed using the Simscape Electrical PV component block. The solar PV system is designed using the Simscape Electrical PV component block.

The PV array is the key renewable energy source of the proposed HES system. The developed model is designed with 300 series-connected cells and 8 parallel-connected modules to achieve the desired electrical output characteristics. The PV model is derived from the electrical characteristics of a realistic PV cell, such as temperature dependence, diode characteristics, and current-voltage relationship.

The simulation is carried out using the following key parameters: $I_{sc} = 3.27$A, $K_I = 0.0017$A/K, and $T_{ref} = 298$k. A band-gap energy of 1.1 eV, a diode ideality factor of 1.6, and reverse saturation current of 2.0793×10^{-6}A is used in the model. The PV system is connected to a 500 V DC bus with a steady power and voltage regulation provided by a regulated DC/DC converter. The PV output voltage, current and power are simulated and monitored during the simulation to evaluate the performance of the renewable energy generation system and its performance under various operating conditions.



Parameters

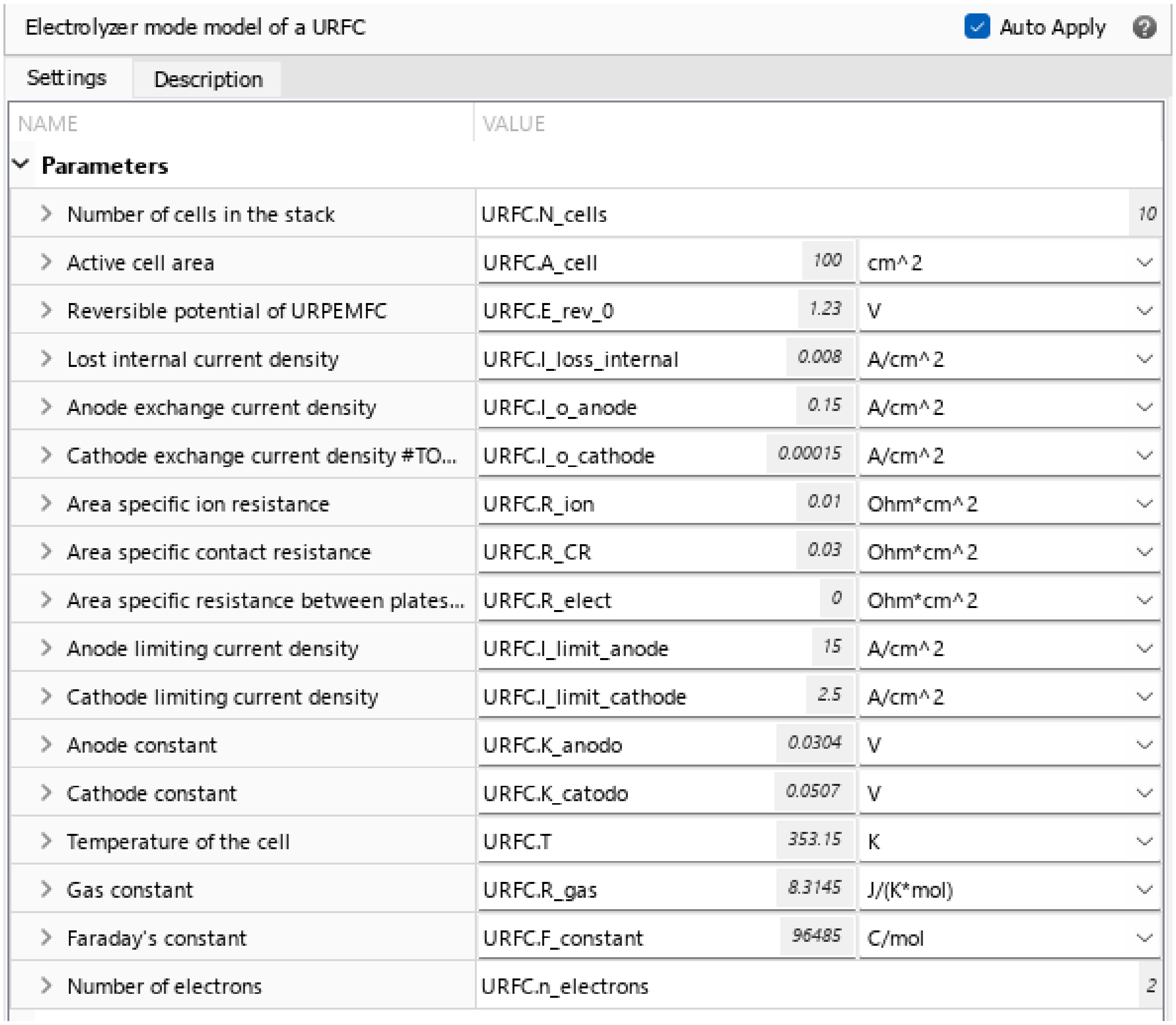
NAME	VALUE		
Nps - Number of PV modules in parallel...	PV.N_ps	8	
Nss - Number of PV cells in series conn...	PV.N_ss	300	
T - Threshold voltage proportional to TS	PV.T_ps	298	K
Tr - Reference temperature	PV.Tr	298	K
Isc - Short circuit current at Tr	PV.Isc	3.27	A
KI - Short circuit current temperature co...	PV.KI	0.0017	A/K
Ior - Irs at Tr	PV.Ior	2.0793e-06	A
Ego - band gap energy of the semicond...	PV.Ego	1.1	V
A - factor. cell deviation from de ideal p...	PV.A	1.6	

Figure 5. PV System parameter

5.2.2 Electrolyzer

MATLAB/Simulink was used to implement the electrolyzer subsystem using the Unitized Regenerative Fuel Cell (URFC) electrolyzer mode block in the Simscape Electrical environment. If excess PV energy is available to the load, the surplus energy is fed to the electrolyzer to split water into hydrogen. The hydrogen produced is then stored as an energy carrier in storage for future use.

The electrolyzer stack consists of 10 cells and an active cell area of 100 cm(^2). The reversible potential of the URPEMFC electrolyzer will be fixed at 1.23 V. Internal current density of 0.008A/cm(^2), anode exchange current density of 0.15A/cm(^2), and cathode exchange current density of 0.00015A/cm(^2) are the model's parameters. The contact resistance and area-specific ion resistance are 0.03Ω·cm(^2) and 0.01Ω·cm(^2), respectively. Also, the limiting current density of the cathode is 2.5A/cm(^2) and that of the anode is 15A/cm(^2). The Faraday's constant is 96485 C/mol, the gas constant is 8.3145 J/Kmol and the cell operating temperature is 353.15 K. These parameters are applied to simulate the electrochemical performance, voltage performance, hydrogen generation and time-varying operational behaviour of the electrolyzer in the hydrogen energy storage configuration



Parameters

NAME	VALUE		
Number of cells in the stack	URFC.N_cells	10	
Active cell area	URFC.A_cell	100	cm^2
Reversible potential of URPEMFC	URFC.E_rev_0	1.23	V
Lost internal current density	URFC.I_loss_internal	0.008	A/cm^2
Anode exchange current density	URFC.I_o_anode	0.15	A/cm^2
Cathode exchange current density #TO...	URFC.I_o_cathode	0.00015	A/cm^2
Area specific ion resistance	URFC.R_ion	0.01	Ohm*cm^2
Area specific contact resistance	URFC.R_CR	0.03	Ohm*cm^2
Area specific resistance between plates...	URFC.R_elect	0	Ohm*cm^2
Anode limiting current density	URFC.I_limit_anode	15	A/cm^2
Cathode limiting current density	URFC.I_limit_cathode	2.5	A/cm^2
Anode constant	URFC.K_anodo	0.0304	V
Cathode constant	URFC.K_catodo	0.0507	V
Temperature of the cell	URFC.T	353.15	K
Gas constant	URFC.R_gas	8.3145	J/(K*mol)
Faraday's constant	URFC.F_constant	96485	C/mol
Number of electrons	URFC.n_electrons	2	

Figure 6. Electrolyzer Parameter

5.2.3 Hydrogen Storage Reservoir

The hydrogen storage reservoir is simulated in MATLAB/Simulink to store the hydrogen produced by the electrolyzer and utilize it in the fuel cell when renewable power is not sufficient. The integrated framework's hydrogen flow balance between production and consumption serves as the foundation for the storage concept. To find the entire quantity of hydrogen contained in the storage tank depends on the continuously measured electrolyzer hydrogen flow.

The hydrogen flow signal (H_2_Flow) is sent to an integrator block to calculate the total amount of hydrogen produced (H_2_Produced) as illustrated in the simulation model. The model also contains the maximum and minimum hydrogen storage level limits (H2_Max_LVL) and (H2_Min_LVL). Overcharging and excessive depletion of the hydrogen tank during system operation is prevented by comparator and stop control blocks. The hydrogen storage subsystem thus provides for safe management of hydrogen, continuous monitoring of hydrogen production and flow rate, and operational reliability of the fuel cell under different renewable generation and load demand conditions.

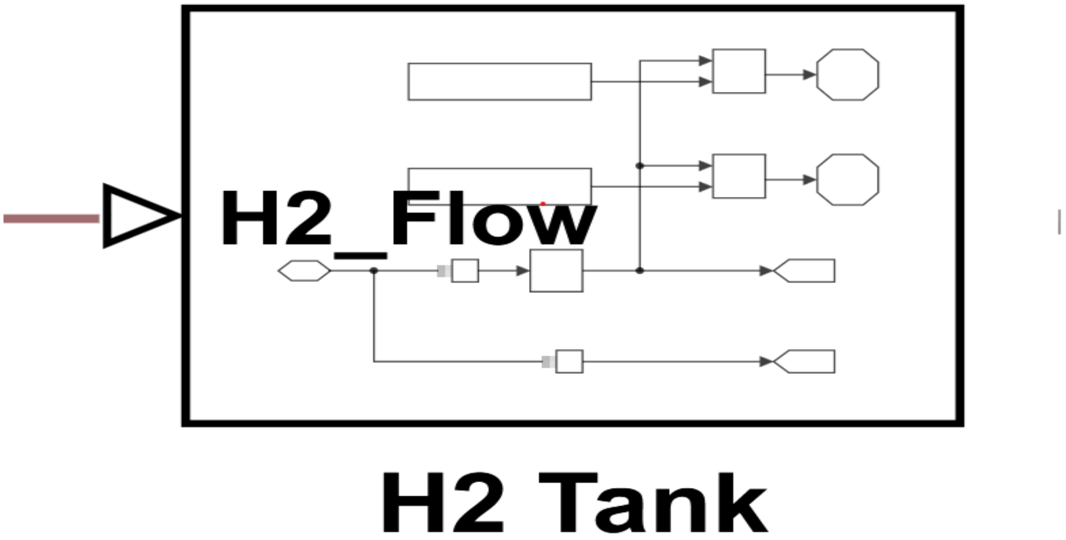
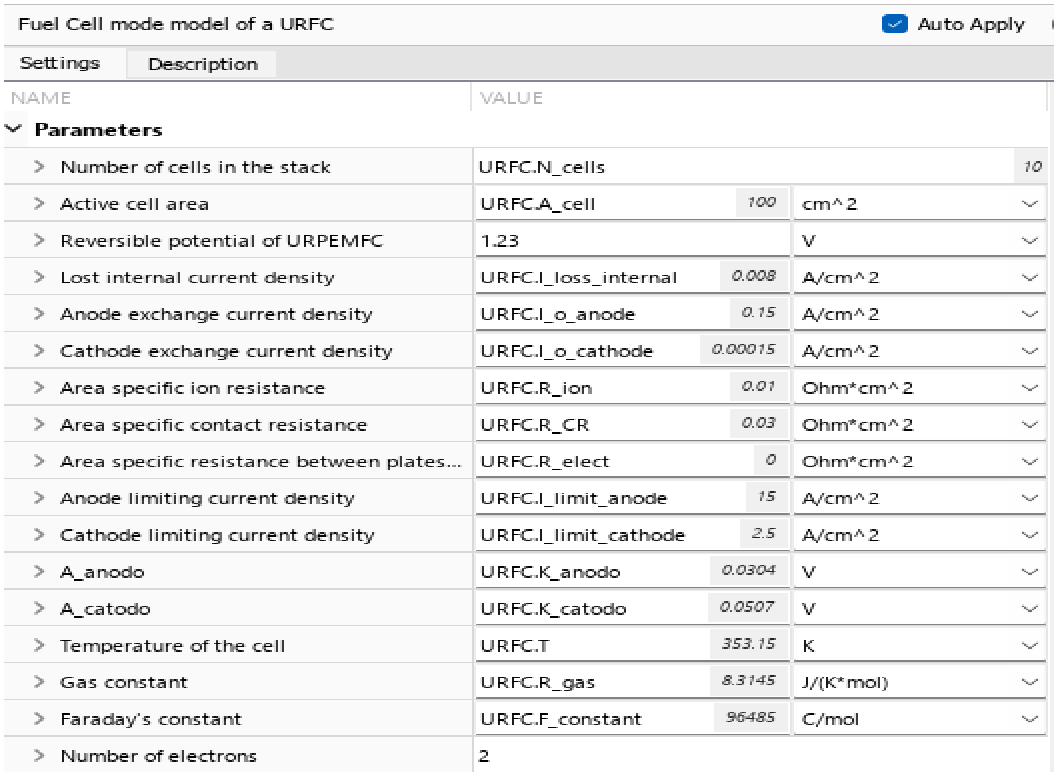


Figure 7. MATLAB/Simulink implementation of the hydrogen storage subsystem showing hydrogen flow integration, storage level monitoring, and operational protection limits for safe hydrogen management.

5.2.4 Fuel cell

The fuel cell generates electricity in the hybrid system when solar PV production is lower than the required load demand. If renewable energy generation is insufficient, the generated electrical power is fed into the DC bus to meet load requirements and improve system stability.

Ten cells make up the fuel cell stack, which has an active cell area of 100 cm^2. The internal current density is lost is 0.008 A/cm (^2), 1.23 V is the reversible potential. The current densities of the anode and the cathode are 0.15 A/cm(^2) and 0.00015 A/cm(^2) respectively. The contact resistance and area-specific ion resistance are 0.03 Ω·cm(2) and 0.01 Ω·cm(2), respectively. The anode limiting current density is 15 A/cm(^2) and cathode limiting current density is 2.5 A/cm(^2). The temperature of the cell is 353.15 K, the gas constant of the cell is 8.3145 J/mol K and the Faraday constant is 96485 C/mol..



Fuel Cell mode model of a URFC

Parameters

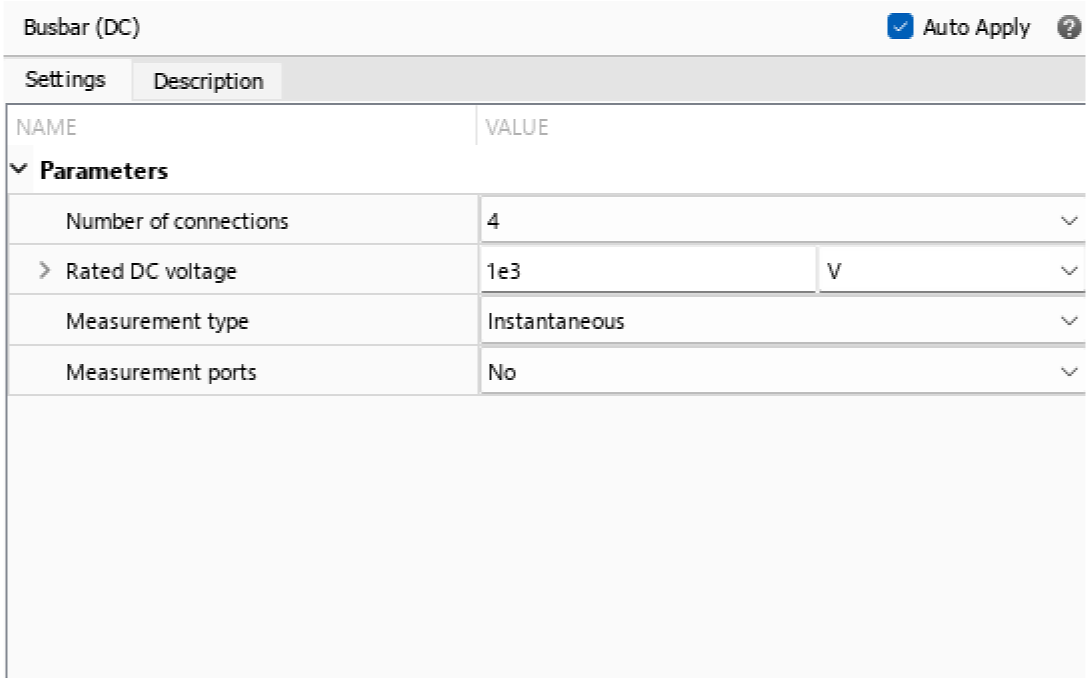
NAME	VALUE		
Number of cells in the stack	URFC.N_cells	10	
Active cell area	URFC.A_cell	100	cm^2
Reversible potential of URPEMFC	1.23		V
Lost internal current density	URFC.I_loss_internal	0.008	A/cm^2
Anode exchange current density	URFC.I_o_anode	0.15	A/cm^2
Cathode exchange current density	URFC.I_o_cathode	0.00015	A/cm^2
Area specific ion resistance	URFC.R_ion	0.01	Ohm*cm^2
Area specific contact resistance	URFC.R_CR	0.03	Ohm*cm^2
Area specific resistance between plates...	URFC.R_elect	0	Ohm*cm^2
Anode limiting current density	URFC.I_limit_anode	15	A/cm^2
Cathode limiting current density	URFC.I_limit_cathode	2.5	A/cm^2
A_anodo	URFC.K_anodo	0.0304	V
A_catodo	URFC.K_catodo	0.0507	V
Temperature of the cell	URFC.T	353.15	K
Gas constant	URFC.R_gas	8.3145	J/(K*mol)
Faraday's constant	URFC.F_constant	96485	C/mol
Number of electrons	2		

Figure 8. Fuel Cell Parameter

5.2.5 DC Bus

The DC bus dynamics were represented through MATLAB/Simulink as the central power exchange interface of the proposed hydrogen-integrated renewable energy system. The DC bus connects the solar PV system, electrolyzer, fuel cell, load, and converter systems within a common electrical platform. It regulates the power flow between system components and maintains dynamic response performance under varying renewable generation and load demand conditions.

As shown in the simulation model, the DC bus is configured with four electrical connections and a rated DC voltage of 500 V. The measurement type is selected as instantaneous to continuously monitor the dynamic voltage behavior during system operation. The DC bus is the main interface for the exchange of energy in the hybrid system, which is used to coordinate energy transfer between the renewable energy sources, hydrogen production, hydrogen consumption, and load demand in order to ensure stable operation of the system. During excess renewable generation, the DC bus transfers surplus power to the electrolyzer for hydrogen production, whereas during renewable energy deficit conditions, the fuel cell supplies power back to the DC bus to support load demand and improve voltage stability.



NAME	VALUE	
Parameters		
Number of connections	4	
Rated DC voltage	1e3	V
Measurement type	Instantaneous	
Measurement ports	No	

Figure 9. DC Bus Parameter

5.3 System Integration

The proposed hydrogen energy storage system is designed as an integrated renewable energy system in MATLAB/Simulink using Simscape Electrical environment. The whole system is simulated in a single simulation platform, including the solar PV array, the DC/DC converters, the DC bus, the electrolyzer, the hydrogen storage tank, the fuel cell, the load, and the control units. The DC bus serves as a common power exchange bus between the PV array, electrolyzer, hydrogen storage system, fuel cell, and load, facilitating seamless energy transfer and stable power balancing across the integrated renewable energy system, and coordinates hydrogen production, hydrogen storage, and electricity supply.

Through a controlled DC/DC converter, the solar PV system supplies electricity to the DC bus when it is in operation. The additional energy supply to the electrolyzer for storage and hydrogen generation if the PV system produces more electrical energy than is needed. This strategy lessens the curtailment of renewable energy and makes it possible to efficiently utilise excess solar energy that could otherwise be lost. If the PV generation is not enough, however, The fuel cell will utilize stored hydrogen to produce energy and support the operation of the DC bus. Additionally, the integrated model features voltage sensors, current sensors, hydrogen flow monitoring blocks, and power measurement units to continuously assess the performance of the system, renewable energy smoothing, hydrogen utilization, and DC bus stability under dynamic operating conditions.

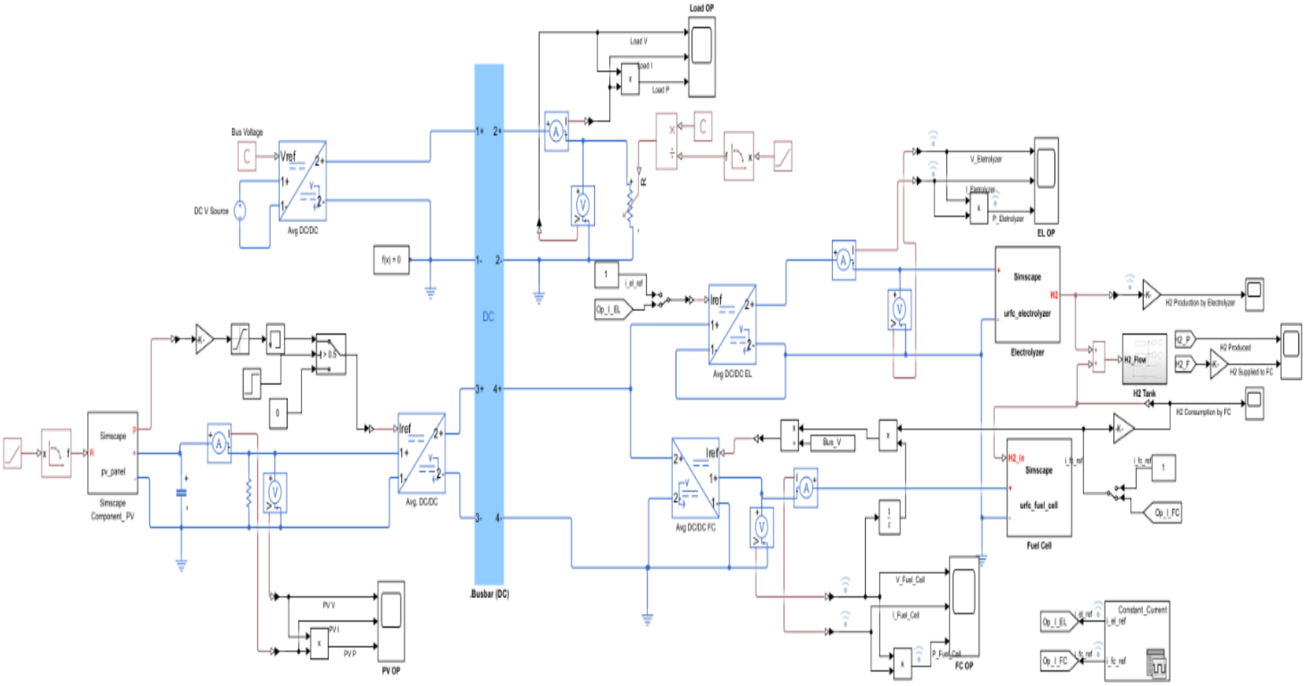


Figure 10. All Subsystems connected MATLAB Model

6 Energy Management and Optimization

6.1 Energy Management Strategy

An optimization method was used in MATLAB/Simulink based on the developed mathematical formulation and energy management strategy to optimize the operation of the hydrogen production system, hydrogen storage system, and fuel cell system under different renewable generation and load demand conditions.

A rule-based optimization method is applied to coordinate the operation of the electrolyzer and fuel cell in this thesis. When PPV>Pload, the electrolyzer is then switched on to absorb any surplus renewable energy and to generate hydrogen. The electrolyzer is then switched on to absorb any surplus renewable energy and to generate hydrogen, when PPV<Pload. The fuel cell is turned on to compensate for the lack of power from the stored hydrogen. This method is chosen because it is easy, low computation and can be used for validating the dynamic coordination of the proposed hydrogen energy storage system in MATLAB/Simulink.

Following the implementation of the component models, the developed strategy controls the power distribution between renewable energy generation and loads, fuel cell, and hydrogen retention system. The control system constantly assesses the renewable energy generation and decides if it is better to store the energy as hydrogen or to use the stored hydrogen to generate electricity. When the electricity generated by the PV system is greater than the electricity required by the load, the electrolyzer will be activated, and the extra electricity will be used to electrolyse ammonia to produce hydrogen gas. The hydrogen so created is then sent to the hydrogen storage tank for later use.

When renewable power generation is insufficient to meet the demand, the fuel cell is turned on to produce power from the stored hydrogen. The hydrogen flow signal (H2_Flow) is integrated to determine the total volume of hydrogen produced in the storage tank as displayed in the hydrogen storage control subsystem. The model also incorporates limits on hydrogen storage level (H2_Max_LVL) and hydrogen storage level minimum (H2_Min_LVL) to ensure safe hydrogen storage operation. The stable and reliable energy management is achieved by the use of comparator and stop control blocks, which prevent hydrogen overcharging and excessive depletion during system operation.

6.2 Optimization Objectives

The proposed hybrid PV–hydrogen system is able to meet the primary optimization goals of efficiency, low dependency on traditional energy sources, hydrogen optimization and stable power supply. The PV system, electrolyzer, hydrogen storage tank, and fuel cell can be integrated into a system that allows for efficient use of renewable energy under different operating conditions. This allows for efficient production of hydrogen from excess renewable energy, and its storage for later use, thereby optimizing overall energy utilization and minimizing losses.

The synergistic integration of the fuel cell and the electrolyzer further improves the reliability and stability of the system, ensuring an uninterrupted power supply during variations in generation and demand. When managed properly, hydrogen production, storage, and consumption are balanced to improve the long-term operational performance and lower the energy cost. In general, the energy management strategy is able to confirm the stable, efficient, and sustainable operation of the integrated renewable energy system. The optimization goal of this study is to minimize the fluctuation of renewable energy, loss of hydrogen energy, deviation of DC bus voltage, and enhance the utilization of renewable energy. The objective function can be expressed as:

$$minJ=w1\sum|PPV-Pload|+w2\sum|Vdc-Vdc,ref|+w3\sum Ploss-w4\sum H2,stored \quad (48)$$

The optimization is subject to the power balance constraint:

$$\boldsymbol{P_{PV}+P_{FC}+P_{grid}=P_{load}+P_{EL}} \quad (49)$$

hydrogen storage limits:

$$\boldsymbol{H_{2,min}\leq H_2\leq H_{2,max}} \quad (50)$$

and DC bus voltage limits:

$$\boldsymbol{V_{dc,min}\leq V_{dc}\leq V_{dc,max}} \quad (51)$$

where $P_{PV}$is the photovoltaic power, $P_{load}$is the load demand, $V_{dc}$is the DC bus voltage, $V_{dc,ref}$is the reference DC bus voltage, P_{loss}represents system losses, $H_{2,stored}$is stored hydrogen, and $w_1, w_2, w_3, w_4$are weighting factors.

6.3 Optimization Techniques

Renewable–hydrogen hybrid systems are optimized using several optimization techniques to improve system efficiency, manage energy use, and reduce operating expense. Under system constraints, LP and MILP methods are widely used to solve energy scheduling problems, energy storage operation scheduling problems, and to minimize the total cost of the system. Elmasry et al. (2024) found that stochastic linear optimization models solved by the CPLEX solvers in the GAMS software are effective solutions for hydrogen-based energy systems and uncertainty management. Likewise, Irham et al. (2024) noted that linear optimization is widely used for operational evaluation, energy dispatch, and economic and technical analysis.

Renewable energy applications also make use of different metaheuristic approaches, including GA and PSO algorithms, which are effective in solving nonlinear and multiobjective optimization problems. Samy et al. (2020) have shown that the optimization of the operational efficiency and optimization of power generation in PV–fuel cell hybrid systems can be achieved using GA-based optimization. Irham et al. (2024) also stated that PSO is very effective in optimizing the size, power control, and energy scheduling of H-RES. Furthermore, hybrid optimization methods like PSO-GWO and Hybrid GA–PSO algorithms have been introduced to enhance operational reliability, cost savings, and system stability of renewable hydrogen systems (Irham et al., 2024).

7 Results and Discussion

7.1 Simulation Results

The simulation results and performance evaluation of the proposed grid-integrated hydrogen energy storage system developed in MATLAB/Simulink (R2024b) using Simscape Electrical environment are presented in this chapter. The coordinated operation of the solar power, electrolyzer, hydrogen storage tank, fuel cell, DC bus, and load under various operating conditions is analyzed. The findings show that the energy management system can successfully manage the renewable energy generation and load demand by transforming excess energy for production during the period of renewable energy surplus and utilizing the stored hydrogen by the fuel cell during the renewable energy shortage period. The integrated hydrogen storage system has been able to increase the effective use of green energy, minimize the fluctuations of renewable supply, and ensure the stability of the DC bus during the simulation process. Furthermore, the synergic operation of the electrolyzer and fuel cell improves the reliability of the system, helps to ensure continuous power generation, and reduces the need for external grid support. The simulation results overall validate the effectiveness of the proposed hybrid PV–hydrogen energy storage system for smoothing the renewable energy, efficient utilization of hydrogen energy, and grid stability for future renewable energy integrated smart grid applications.

Table 3. Comparisons

Metric	**Without hydrogen storage**	**With hydrogen storage**
DC bus voltage stability	**lower**	**improved**
Renewable curtailment	**higher**	**reduced**
Power smoothing	**limited**	**improved**
Hydrogen utilization	**not applicable**	**active**
Backup power support	**unavailable**	**available**

The comparison validates the hydrogen storage's ability to smooth out the renewable energy supply and demand by absorbing excess PV power when it is generated and delivering stored energy when it is needed via the fuel cell.

7.1.1 Power Curves

The power curves obtained show the effective operation and operational optimization characteristics of the proposed hybrid PV–hydrogen energy storage framework. The PV system exhibits optimal performance in the first curve, with the output voltage, current, and power rising and then leveling off, indicating the successful optimization of the system and efficient extraction of maximum power from the solar source. The second curve is the fuel cell operation curve, which is used for fuel cell operation when renewable generation is low, providing stable power support and maintaining continuous power supply to enhance system reliability. The third curve shows the power characteristics of the electrolyzer, where the excess PV power is effectively used for hydrogen production by controlling the operation, highlighting the efficient energy conversion and storage capacity. In addition, the results also show that the system remains stable when operating under a constant current, which means that the control coordination between the PV source, electrolyzer, hydrogen storage system, and fuel cell is correct during the whole simulation time.

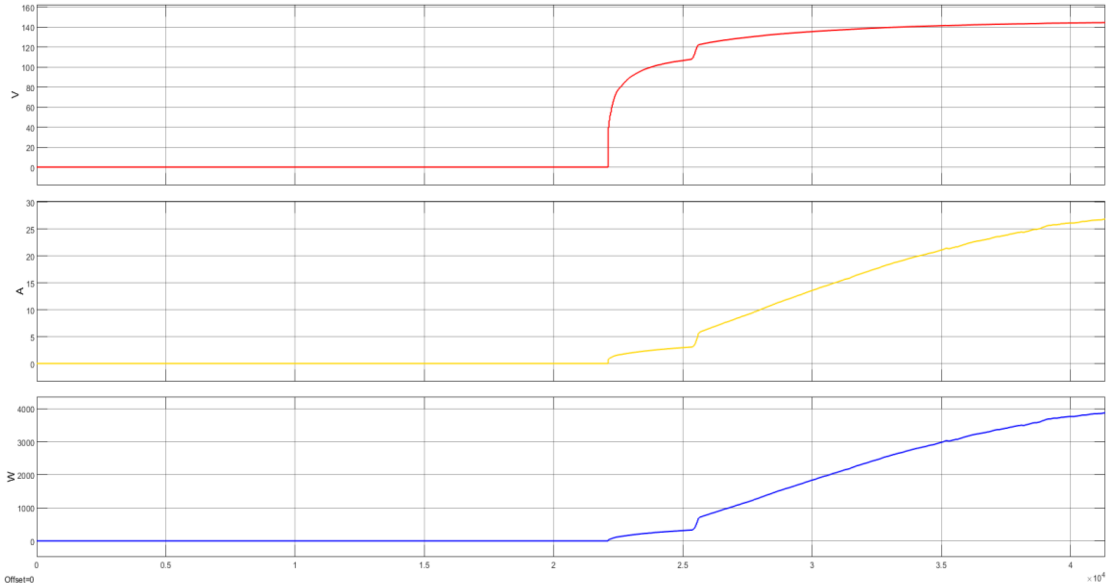


Figure 11. Power Curves in Optimized System, Electrolyzer, Constant Current mode

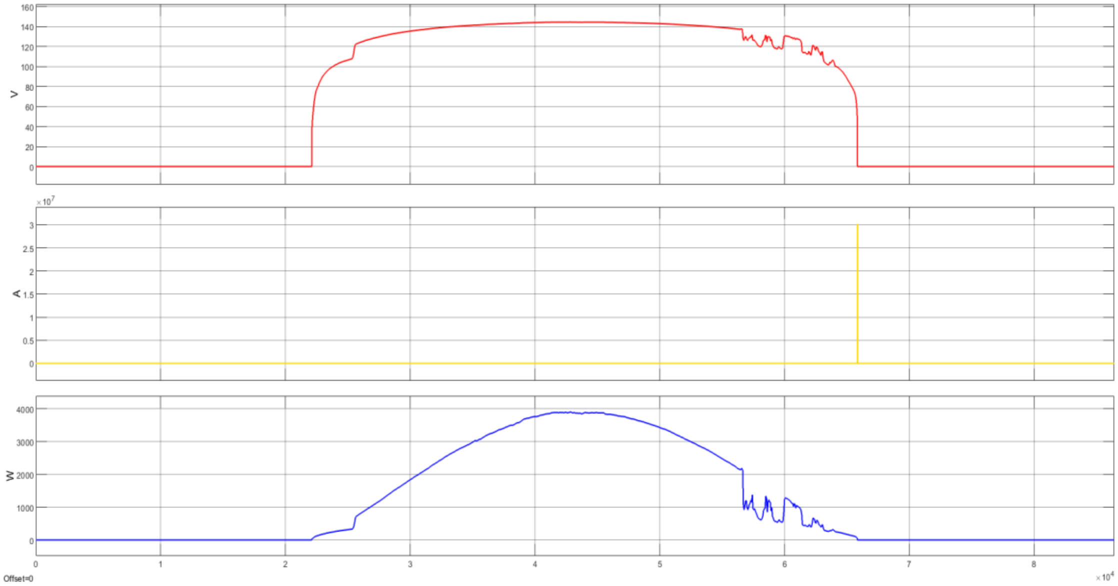


Figure 12. Power curves in Fuel cell Condition

7.1.2 Hydrogen production

After analysing the electrical power characteristics, the ability of the system to produce and store hydrogen is assessed. The results of the hydrogen production show how well the suggested hydrogen energy storage system works. The top plot shows a gradual increase in hydrogen production over the course of the simulation, indicating that the electrolyser process is successfully converting excess solar power into hydrogen. The electrolyzer can effectively store excess PV generation for future use, which decreases renewable energy curtailment and improves renewable energy efficiency. The hydrogen utilization efficiency of the proposed system reached approximately 70–80% under dynamic simulation conditions. The hydrogen delivered to the fuel cell, where a steady hydrogen delivery rate is maintained throughout fuel cell operation, is depicted in the lower curve. The coordinated operation of the system ensures the continuous energy balance, including hydrogen production, storage, and fuel cell utilization.

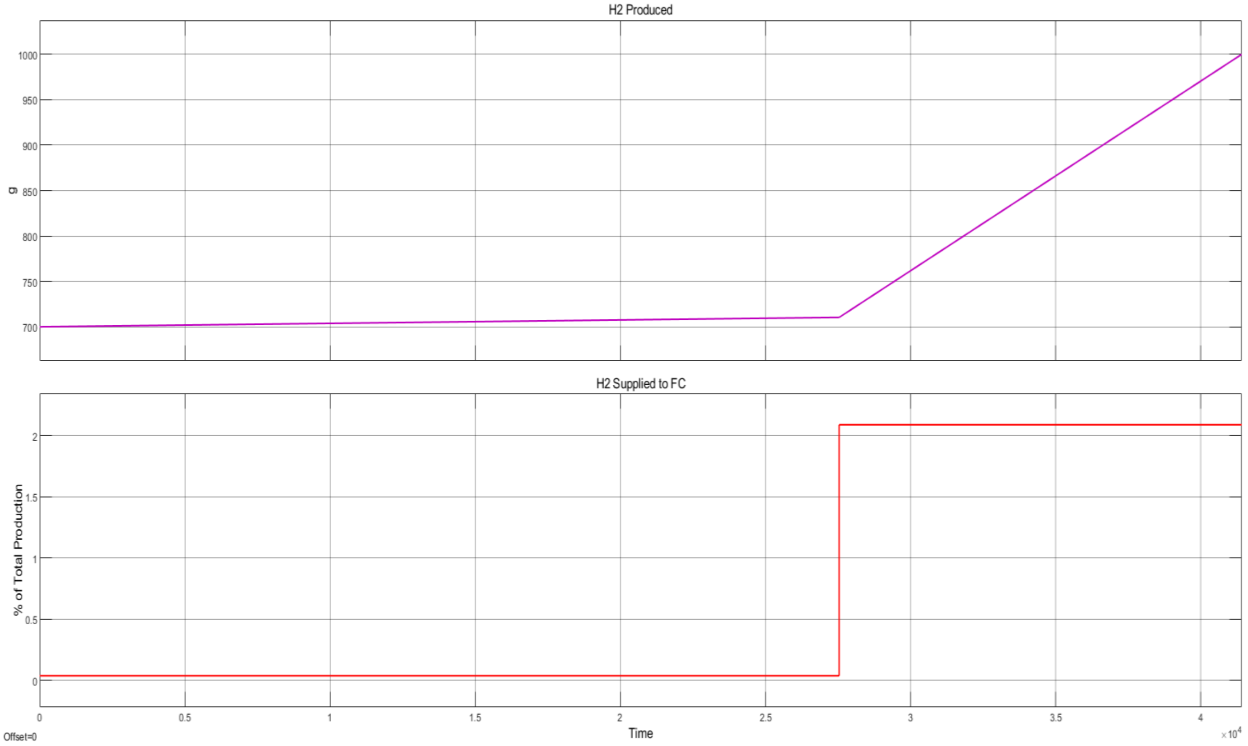


Figure 13. Hydrogen Produced and Supplied to Fuel Cell

7.1.3 Hydrogen consumption

To further assess the effectiveness of the hydrogen storage system, the hydrogen consumption behavior during fuel cell operation is analyzed. The hydrogen consumption results show how the stored hydrogen is being used in the proposed hybrid energy system. The top plot displays the variation of hydrogen storage capacity during the simulation, with the amount of hydrogen initially rising as it is continuously produced by the electrolyzer, and then fluctuating as the system's energy demand changes. The bottom curve is the hydrogen consumption ratio provided to the fuel cell. Hydrogen is used in a controlled and stable way during fuel cell operation to enable power generation and system reliability. The results confirm that fuel cells efficiently store and use hydrogen, which helps the system control energy distribution and run smoothly.

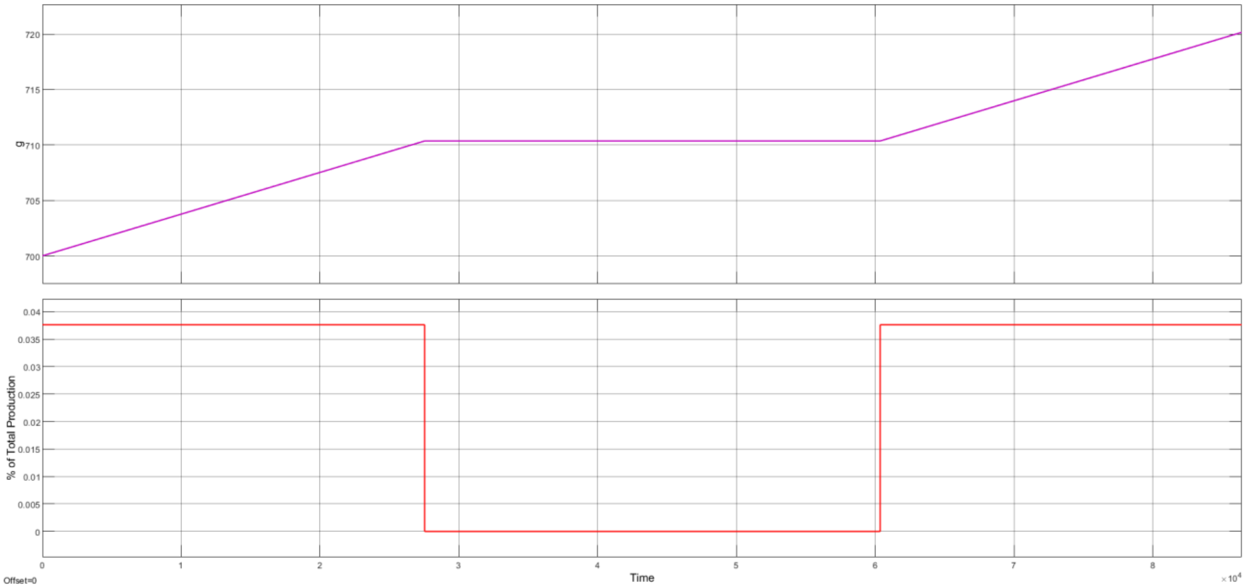


Figure 14. Hydrogen Consumption in Fuel Cell for producing power

7.1.4 DC bus voltage stability

In addition to hydrogen management performance, voltage regulation capability is evaluated through DC bus stability analysis. DC bus voltage stability evaluation further validates the system robustness of the proposed hybrid renewable energy system under the optimized and fuel cell operating conditions. The voltage stability of the DC bus is maintained using an optimized control method. During the simulation period and the result is shown as the first curve, which shows that the voltage is kept at a constant value. The second curve shows the fuel cell operating mode, in which the fuel cell current and power output change to meet the load demand, and the DC bus voltage is kept constant at 500 V. When renewable power sources are insufficient, the fuel cell dynamically compensates by providing extra electrical power to the DC bus to maintain the voltage level and to provide continuous electrical power under different operating conditions.

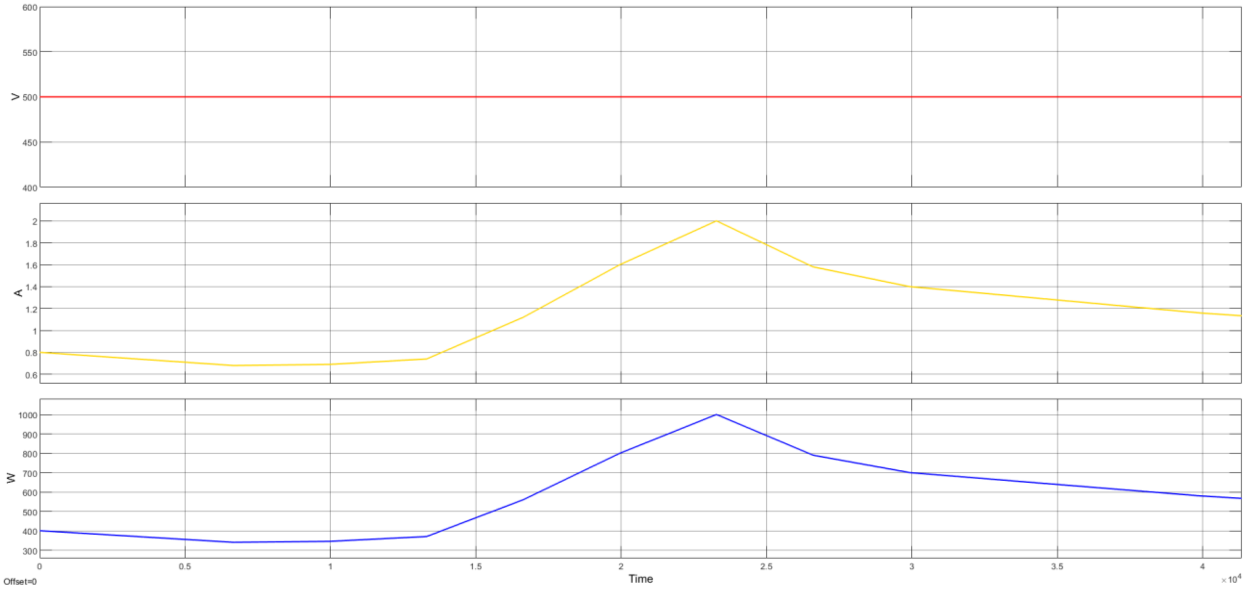


Figure 15. DC Bus Voltage Stability in Optimized with load

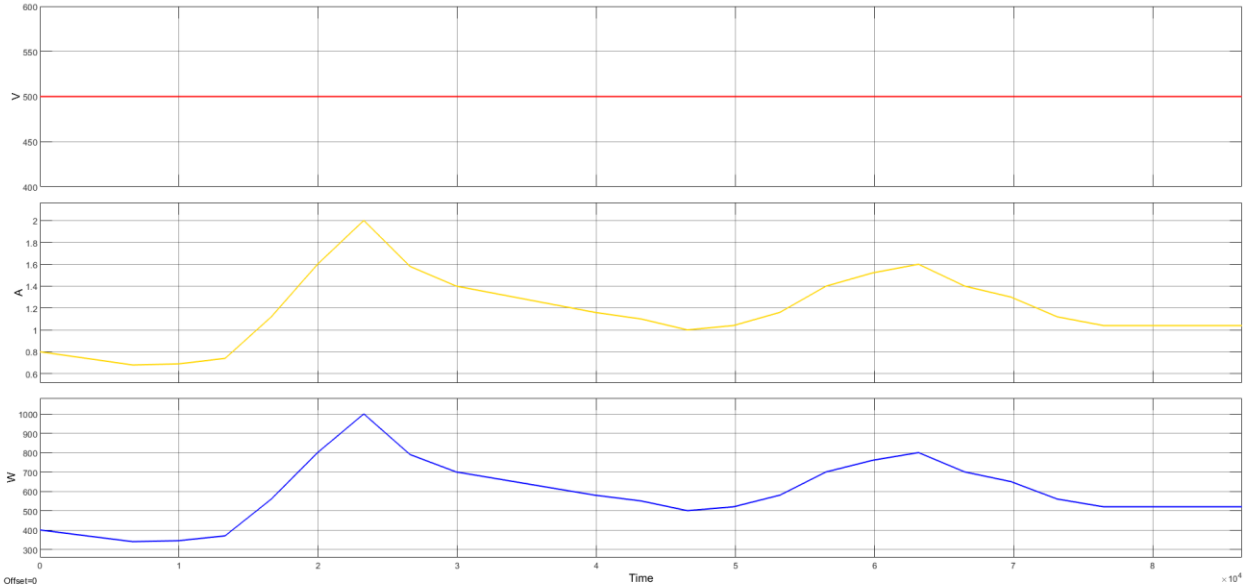


Figure 16. DC Bus Voltage Stability with Load and Fuel Cell

7.2 Performance Evaluation

According to operational results, the overall output is evaluated in terms of efficiency, renewable smoothing capability, and operational stability. The system performance evaluation indicates good operational efficiency of the proposed model, stable renewable energy integration, and enhanced grid support capability. The efficient energy conversion was realized by the coordinated operation of the photovoltaic array, the electrolyzer, the hydrogen storage system, and the fuel cell system. To store surplus renewable energy when it is generated and to release stored energy when renewable energy is in deficit, hydrogen energy storage and coordinated power management were implemented. For the conditions of dynamic simulation, the hydrogen utilization efficiency of the proposed system was reached at about 70–80%. This synchronized operation minimized the fast power fluctuations at the DC bus and enhanced the smoothing function of the integrated system for renewable energy. If there is too much renewable energy, The electrical power produced by the PV system can be converted into hydrogen and stored for later energy supply when renewable generation is unavailable. During these times, electrical energy is produced by the fuel cell using the stored hydrogen as fuel. The control method optimizes the energy flow to the PV system, the electrolyzer, the fuel cell and the load, while operating under different conditions, which helps to stabilize the grid and control the DC bus voltage. Thus, the power fluctuation was reduced by around 20–25% at the grid side, which ultimately increased the operational stability of the entire renewable energy system. The overall performance of the developed system was found to be reliable and good utilization of renewable energy resources with stability and flexibility of the integrated power system.

7.3 Comparison With and Without Hydrogen Storage

The comparison of the systems with and without hydrogen storage emphasises how crucial hydrogen energy management is to raising the hybrid renewable energy system's overall performance. Without the hydrogen storage, the generation of renewable energy is directly related to the availability of solar energy, which results in intermittent power generation and reduces the capacity to supply a steady stream of electricity when solar energy is not generated. This operational coordination improved renewable energy utilization and reduced excess renewable energy curtailment by approximately 15–25%. On the other hand, the implemented system using hydrogen storage shows better energy utilization as the excess renewable energy is stored by the electrolyzer and the stored energy is used by the fuel cell when needed. This synchronized hydrogen charging and discharging process helps to maintain an uninterrupted power flow and smooth out the photovoltaic generation fluctuations. This, therefore, mitigates the intermittency effects of renewables, enhancing the reliability of the system and energy supply under different operating conditions. Hydrogen storage also helps to improve voltage regulation within the DC bus and the smoothness of the power regulation under different operating conditions. In addition, the hydrogen storage system is integrated, providing greater operational flexibility and facilitating optimal management of renewable energy, thus making the proposed configuration more appropriate for stable and sustainable power generation applications.

8 Conclusion and Future Work

8.1 Conclusions

In this study, a hybrid renewable energy system integrated with a fuel cell and hydrogen storage technology has been developed, simulated, and evaluated. The proposed system successfully showed the coordinated operation of PV generation, hydrogen synthesis by electrolysers, hydrogen storage and fuel cell power generation during various modes of operation. The simulation output displayed that the hydrogen energy management strategy could be successfully applied to minimize the variability of sustainable power sources and ensure stability of the DC bus under different loads. Utilizing hydrogen storage improved overall energy management performance, reduced the fluctuation of renewable energy sources, and improved system reliability. The results also demonstrated the effectiveness of the optimized control strategy in regulating the power flow and maintaining the stability of the hybrid system.

8.2 Contributions

The study's most significant achievement is the development of a model of an integrated fuel cell/hydrogen storage system for renewable energy applications. An electrolyser and fuel cell were used in conjunction to successfully implement a hydrogen production and consumption framework for energy balancing. Additionally, the optimization of the system's performance through efficient power management and control strategies led to better operational stability and energy utilization, contributing to the overall success of the project. The study also highlighted the potential for hydrogen storage to help balance fluctuations in renewable energy sources and improve power continuity, enhancing the development of efficient and dependable hybrid energy systems.

8.3 Future Work

The simulation model could be further developed by implementing it on hardware and testing it in real time to validate the simulation results in actual operating conditions. Future research could involve the practical application of the hybrid renewable hydrogen system to the real grid to assess the system's performance under actual grid disturbances and load fluctuations. Furthermore, advanced optimization techniques using artificial intelligence, such as machine learning and adaptive control algorithms, can be utilized to enhance energy management, predictive control, and system efficiency in large-scale renewable energy systems.

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Appendix

MATLAB code: microgrids parameter:

```
load("input_data_24h.mat")

URFC = urfc_parameters;
PV = photovoltaic_parameters;
Bus_V = 500;                % [V]
H2_Max_LVL = 1000;                  % [g]
H2_Min_LVL = 0.2*H2_Max_LVL;    % [g]
URFC_TANK.IniLvl = 0.7*H2_Max_LVL;    % [g]
```

Photovoltaic_parameters code :

```
classdef photovoltaic_parameters < handle
   properties (Constant)
   % Physical constants
   Q = 1.6e-19; % Elementary charge
   K = 1.38e-23; % Boltzmann constant
   % Photovoltaic parameters
   N_ps = 8;           % Number of panels in parallel
   N_ss = 300;         % Number of panels in series
   T_ps = 298;         % Temperature
   Tr = 298;           % Reference temperature
   Isc = 3.27;         % Short circuit current at Tr
```

```
  Kl = 0.0017;        % Short circuit current temperature coeff
  Ior = 2.0793e-6;    % Ior - Irs at Tr
  Ego = 1.1;          % Band gap energy of the semiconductor
  A = 1.6;            % Factor. cell deviation from de ideal pn junction
  end
end
```

URFC_parameters :

```
classdef urfc_parameters < handle
  % urfc_parameters - Class representing the parameters of the URFC model.
  %
  %   Properties:
  %      - R_gas: Gas constant [J/(mol*K)]
  %      - F_constant: Faraday's constant [C/mol]
  %      - n_electrons: Number of electrons involved in the reaction [dimensionless]
  %      - N_cells: Number of cells in the stack [dimensionless]
  %      - A_cell: Active cell area [cm^2]
  %      - E_rev_0: Reversible potential of URPEMFC [V]
  %      - I_loss_internal: Lost internal current density [A/cm^2]
  %      - I_o_anode: Anode exchange current density [A/cm^2]
  %      - I_o_cathode: Cathode exchange current density [A/cm^2]
  %      - R_ion: Area specific ion resistance [Ohm*cm^2]
  %      - R_CR: Area specific contact resistance [Ohm*cm^2]
  %      - R_elect: Area specific resistance between plates and connections [Ohm*cm^2]
  %      - I_limit_anode: Anode limiting current density [A/cm^2]
  %      - I_limit_cathode: Cathode limiting current density [A/cm^2]
  %      - K_anodo: Value [V]
  %      - K_catodo: Value [V]
```

```
%     - T: Temperature of the cell [K]
%
%   Example:
%     params = urfc_parameters;
%     gas_constant = params.R_gas;
%     faraday_constant = params.F_constant;

properties (Constant)
  % Gas constant [J/(mol*K)]
  R_gas = 8.3145;
  % Faraday's constant [C/mol]
  F_constant = 96485;
  % Number of electrons involved in the reaction [dimensionless]
  n_electrons = 2;
  % Number of cells in the stack [dimensionless]
  N_cells = 10;
  % Active cell area [cm^2]
  A_cell = 100;
  % Reversible potential of URPEMFC [V]
  E_rev_0 = 1.23;
  % Lost internal current density [A/cm^2]
  I_loss_internal = 0.008;
  % Anode exchange current density [A/cm^2]
  I_o_anode = 0.15;
  % Cathode exchange current density [A/cm^2]
  I_o_cathode = 1.5e-4;
  % Area specific ion resistance [Ohm*cm^2]
  R_ion = 0.01;
```

```
    % Area specific contact resistance [Ohm*cm^2]
    R_CR = 0.03;
    % Area specific resistance between plates and connections [Ohm*cm^2]
    R_elect = 0;
     % Anode limiting current density [A/cm^2]
    I_limit_anode = 15;
    % Cathode limiting current density [A/cm^2]
    I_limit_cathode = 2.5;
    % Value [V]
    K_anodo = 0.0304;
    % Value [V]
    K_catodo = 0.0507;
    % Temperature of the cell [K]
    T = 353.15;
  end
end
```