Formosa Journal of Science and Technology (FJST)
Vol. 5, No. 4, 2026: 1029-1042

Hydrogen Integrated Renewable Energy Storage Stability in Intermittent Solar and Wind Power Systems

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ARTICLE INFO

Keywords: Hydrogen Energy Storage, Renewable Energy, System Stability, Microgrid, Solar Energy, Wind Energy.

Received : 27, February
Revised : 29, March
Accepted: 30, April

ABSTRACT

The intermittency of renewable energy, especially solar and wind power, is a major challenge in maintaining the stability of modern electric power systems, especially in the parameters of frequency, voltage, and supply continuity. This study analyzes the integration of Hydrogen Energy Storage System (HESS) in a solar–wind hybrid microgrid in the southern coastal region of West Java which has characteristics of solar radiation variability and high wind speed. The methods used include dynamic modeling based on nonlinear differential systems for electrolyser components, pressurized hydrogen storage tanks, and fuel cells, as well as stability analysis using a small-signal approach and MATLAB/Simulink-based transient simulation. The results showed that HESS integration was able to significantly reduce power fluctuations by about 40 percent and improve system frequency stability compared to systems without storage. The implementation of a control strategy based on a predictive control model has also been proven to improve the efficiency of energy distribution and system response to changes in load and energy source. Analysis of thermodynamics and fluid mechanics in hydrogen compression processes shows that storage pressures in the mid-range of 30 to 50 bar provide a balance between efficiency and system safety. The study confirms that hydrogen storage technology is an effective solution to improve the stability and flexibility of intermittent renewable energy systems, as well as support the development of sustainable energy systems in regions with high renewable energy penetration

ISSN-E: 2964-6804
DOI: https://doi.org/10.55927/fjst.v5i4.51
https: https://journalfjst.my.id/index.php/fjst

INTRODUCTION

The transition to a sustainable energy system is driving increased penetration of renewable energy sources, particularly solar and wind, in modern electric power systems (Saleh & Hassan, 2024). Both of these energy sources have advantages in terms of availability and low emissions, but the characteristics of intermittency and uncertainty of their production are the main challenges in maintaining system stability. Variations in solar radiation due to atmospheric conditions as well as fluctuations in wind speed cause rapid and unpredictable changes in power, potentially disrupting the balance between generation and load. This imbalance directly affects the operational parameters of the system such as frequency, voltage, and continuity of electrical energy supply.

These problems are becoming increasingly complex in microgrid systems with a high level of renewable energy penetration. Microgrids that rely on a combination of solar and wind sources tend to experience significant power fluctuations on both short and long time scales (Zhang et al., 2024). In the absence of an adequate balancing mechanism, this condition can degrade power quality, accelerate equipment degradation, and increase the risk of system instability. Therefore, an energy storage system is needed that is not only able to store large amounts of energy, but also has the flexibility to respond to system dynamics in real-time.

Hydrogen Energy Storage System emerged as one of the potential solutions to overcome this problem. This system works through the process of converting electrical energy into hydrogen using an electrolyser when there is an excess of energy, then storing it in a pressurized tank, and converting it back into electrical energy using fuel cells when there is an energy shortage. Compared to other storage technologies, hydrogen systems have advantages in long-term storage capacity, high energy density, and the ability to function as a storage medium as well as an energy carrier (Yang et al., 2023).

From the point of view of physical and mechanical engineering, the integration of hydrogen systems in a microgrid involves complex interactions between electrochemical, thermodynamic, and fluid dynamics phenomena (Indrajith et al., 2025). The electrolysis process is influenced by the energy conversion efficiency and material characteristics, while the hydrogen storage process in a pressurized tank involves aspects of fluid mechanics and heat transfer. In addition, the energy conversion in fuel cells is influenced by the dynamics of chemical reactions and the operational conditions of the system. The interaction between these components forms a nonlinear system that requires a dynamic modeling approach to understand the behavior of the system as a whole (Ige et al., 2024).

In the context of power system stability, the existence of a Hydrogen Energy Storage System acts as a power balancer that is able to reduce the deviation between generation and load (Selim et al., 2024). By controlling the flow of energy through the electrolyser and fuel cell, the system can dampen power fluctuations and improve the system's frequency response to interference. To achieve optimal performance, adaptive and predictive control strategies, such as predictive control models, are needed that are able to anticipate changes in system conditions based on the mathematical model used (Schwenzer et al., 2021).

The southern coastal area of West Java was chosen as the study location because it has the characteristics of renewable energy sources that have high potential but are volatile (Fauzia & Makarim, 2024). The combination of tropical solar radiation and coastal wind patterns results in significant energy variability, making it a representative environment to assess the performance of hybrid microgrid systems with hydrogen storage integration. This condition makes the region a relevant case study to evaluate the effectiveness of the Hydrogen Energy Storage System in improving the stability of the power system (Muzammal Islam et al., 2024).

Based on this background, this study is focused on the stability analysis of the solar–wind hybrid microgrid system with the integration of the Hydrogen Energy Storage System through a dynamic modeling approach based on a nonlinear differential system and numerical simulation (Abdelghany et al., 2024a). This study aims to evaluate the system's ability to reduce power fluctuations, improve frequency stability, and optimize system performance through the implementation of appropriate control strategies. Thus, it is hoped that this research can contribute to the development of a more reliable, flexible, and sustainable renewable energy system.

THEORETICAL REVIEW

The development of solar and wind-based renewable energy systems has become a major focus in modern power systems (Roy et al., 2022). However, the intermittent nature of the two energy sources leads to significant power instability, especially in microgrid systems with high penetration of renewable energy. Fluctuations in solar radiation and wind speed result in random and unpredictable power variations, resulting in deviations between generating power and load that have a direct impact on the stability of the system's frequency and voltage.

To address these problems, various energy storage technologies have been developed, including batteries, supercapacitors, and hydrogen-based systems (Soudagar et al., 2024). Among these technologies, the Hydrogen Energy Storage System has advantages in long-term energy storage capacity as well as flexibility in integration with renewable energy systems. The system works through a power-to-hydrogen-to-power mechanism, where electrical energy is converted into hydrogen through an electrolysis process, stored in a pressurized tank, and converted back into electricity using fuel cells when needed.

In the context of microgrids, the integration of hydrogen storage systems has been proven to improve the reliability and stability of the system (Wu et al., 2022). Previous studies have shown that the use of hydrogen as an energy storage medium can reduce power fluctuations and improve the system's ability to respond to load changes. In addition, the combination of hydrogen systems with renewable energy sources allows for the creation of more flexible and self-sufficient energy systems, especially in isolated systems or areas with limited access to the main power grid.

From a modeling perspective, microgrid systems with Hydrogen Energy Storage System integration are generally represented using dynamic models based on nonlinear differential equations (Diabate et al., 2023). This model includes the characteristics of electrolyzers, hydrogen storage tanks, and fuel cells, each of which has different but interconnected dynamics. The complexity of this system demands the use of stability analysis methods that are able to accurately describe system behavior, such as the small-signal stability approach to analyze the system's response to minor disturbances and transient simulations to evaluate system performance under dynamic conditions.

In addition, the control strategy plays an important role in optimizing the performance of hydrogen-based microgrid systems (Sarwar et al., 2024). Conventional approaches are often insufficient to address the high uncertainty in renewable energy systems. Therefore, prediction-based control methods such as predictive control models are widely used because of their ability to anticipate changes in system conditions in real-time. This approach allows for optimal regulation of electrolyzer and fuel cell operation, thereby minimizing power fluctuations and improving overall system efficiency.

Although various studies have shown the great potential of Hydrogen Energy Storage Systems in improving the stability of renewable energy systems, most studies still focus on aspects of energy optimization and power management in general. Studies that specifically integrate dynamic stability analysis, system physics modeling, and specific geographical conditions are still relatively limited. This suggests that there is a need for more comprehensive research that not only considers the technical aspects of the system, but also the characteristics of the energy source at a particular location.

In this context, the southern coastal area of West Java is an area that has significant potential for the development of a hybrid microgrid system based on renewable energy. The characteristics of tropical solar radiation and fluctuating coastal wind patterns make this region a relevant location to study the performance of hydrogen energy storage systems under real conditions (Mirsane et al., 2026). Therefore, this study fills the gap by analyzing the stability of a solar–wind hybrid microgrid system integrated with the Hydrogen Energy Storage System through dynamic modeling and numerical simulation approaches (Abdelghany et al., 2024b).

METHODOLOGY

This study uses a quantitative approach based on mathematical modeling and numerical simulation to analyze the stability of a solar–wind hybrid microgrid system integrated with the Hydrogen Energy Storage System. The methods used include dynamic system modeling, stability analysis, and implementation of control strategies to evaluate system performance as a whole (Brunton et al., 2021a).

System Configuration

The system studied is a hybrid microgrid consisting of renewable energy sources in the form of solar panels and wind turbines, hydrogen-based energy storage systems, and electrical loads. The Hydrogen Energy Storage System consists of three main components, namely the electrolyser as a converter of electrical energy into hydrogen, a pressurized hydrogen storage tank, and a fuel cell as a hydrogen to electrical energy converter.

The energy generated from solar and wind sources will be directly supplied to the load. The excess energy will be flowed to the electrolyser to produce hydrogen, while in energy deficit conditions, the fuel cells will be activated to supply additional power to the system. This scheme allows for dynamic power balance.

Study Location

This study is focused on the southern coastal region of West Java which has the characteristics of high renewable energy variability. The solar radiation profile data and wind speed are represented in the form of time variations to reflect the operational conditions of the system realistically.

Mathematical Modeling of Systems

System modeling is carried out using a nonlinear differential equation approach to represent the dynamics of each component.

a. System Power Balance

The balance of forces in the system is expressed as:

$$\Delta P = P_{solar} + P_{wind} + P_{FC} - P_{EL} - P_{load}$$

where the power deviation is used as the main indicator of system stability (Ammar et al., 2025).

b. Electrolyser Model

The production of hydrogen by electrolyzers is modeled as:

$$\dot{m}_{H2} = \frac{\eta_{el} \cdot P_{el}}{LHV_{H2}}$$

which describes the relationship between the input power and the rate of hydrogen production (Abomazid, 2021).

c. Hydrogen Storage Tank Models

The dynamics of pressure in the storage tank are expressed by:

$$\frac{dP}{dt} = \frac{RT}{v}(\dot{n}_{in} - \dot{n}_{out})$$

This model considers the properties of hydrogen gas as an ideal gas under certain operating conditions.

d. Fuel Cell Models

The output power of a fuel cell is formulated as:

$$P_{FC} = \eta_{FC} \cdot \dot{m}_{H2} \cdot LHV_{H2}$$

which shows the conversion of hydrogen chemical energy into electrical energy.

System Stability Analysis

Stability analysis was performed using a small-signal approach to evaluate the system's response to minor disturbances (Abomazid, 2021b). The frequency dynamics of the system are expressed as:

$$\frac{df}{dt} = \frac{1}{2H} \Delta P$$

Where the constant inertia of the system affects the sensitivity of the frequency change to the power imbalance. In addition, transient simulations are carried out to observe the system's response to load changes and fluctuations in energy sources in real time.

System Control Strategy

To improve system performance, a predictive control model-based control strategy is applied (Brunton et al., 2021). The system model is represented in the form of state-space:

$$x(k+1) = A\,x\,(k) + Bu\,(k) + y(k) = C\,x\,(k)$$

The objective functions of the control are designed to minimize power deviation and energy usage:

$$J = \sum(P_{ref} - P)^n + \lambda_{\mathcal{U}}{}^2$$

This strategy allows for optimal regulation of electrolyzer and fuel cell operations based on predictive system conditions.

System Simulation and Parameters

Simulations are carried out using MATLAB/Simulink to evaluate system performance under various operating conditions. The simulation scenarios include variations in solar radiation and wind speed, changes in electrical loads, as well as surplus and deficit conditions that realistically represent the dynamics of the microgrid system. The system parameters are determined based on the typical values of the microgrid system, including the efficiency of the electrolyser and fuel cell, as well as the storage pressure of hydrogen in the medium range of 30 to 50 bar. The selection of these parameters aims to reflect realistic operational conditions and ensure a balance between energy efficiency and system safety at the microgrid scale.

RESEARCH RESULTS

System Performance Without and With HESS

The simulation results showed that the solar–wind hybrid microgrid system without the integration of the Hydrogen Energy Storage System experienced significant power fluctuations due to the variability of solar radiation and wind speed. The imbalance between generating power and load leads to relatively large frequency deviations as well as slow system responses to changes in operating conditions. On the contrary, after the integration of the Hydrogen Energy Storage System, there has been a significant improvement in system performance. The system is able to absorb excess energy through the electrolyser in surplus conditions and release energy through the fuel cell when there is a deficit. This mechanism results in a more stable power profile and reduces the overall power imbalance.

Power Fluctuation Reduction

The simulation results show that the integration of the Hydrogen Energy Storage System has a significant influence on the reduction of power fluctuations in the solar-wind hybrid microgrid system. Under conditions without HESS, the system output power variation is in the range of -25 kW to +25 kW to the reference value, so that the total fluctuation amplitude reaches:

$$A_{without} = P_{max} - P_{min} = 25 - (-25) = 50 \text{ kW}$$

These fluctuations show that there is a considerable power imbalance due to the variability of renewable energy sources. After HESS integration, the system demonstrates the ability to dampen fluctuations through energy storage and release mechanisms. The range of power deviation is reduced to about −15 kW to +15 kW, so that the amplitude fluctuates to:

$$A_{with} = 15 - (-15) = 30 \text{ kW}$$

Based on these values, the percentage reduction in power fluctuations is calculated as:

$$Reduction = \frac{50 - 30}{50} x\ 100\% = 40\%$$

In addition, an analysis of the rate of power change shows that a system without HESS has a relatively sharp change in power. For example, in a 10-second time interval there is a change in power from 30 kW to 50 kW, so the ramp rate is calculated as:

$$RR_{without} = \frac{50 - 30}{10} = 2\ kW/s$$

After HESS integration, the power change at the same time interval becomes more controlled, e.g. from 34 kW to 44 kW, so that:

$$RR_{with} = \frac{44 - 34}{10} = 1\ kW/s$$

This shows that there is a decrease in the ramp rate as follows:

$$RR\ reduction = \frac{2 - 1}{2} x\ 100\% = 50\%$$

These findings indicate that in addition to lowering the amplitude of power fluctuations, the Hydrogen Energy Storage System also effectively refines the power change profile over time. With a 40 percent reduction in fluctuation amplitude and a 50 percent decrease in ramp rate, the system shows a significant improvement in power quality and operational stability.

Increased Frequency Stability

The integration of the Hydrogen Energy Storage System also has a significant impact on the stability of the system's frequency. The simulation results show that the frequency deviation due to load disturbances and fluctuations in energy sources can be significantly suppressed. The system's frequency response becomes faster back to nominal state compared to a system without storage. This shows that the hydrogen system acts as an effective energy buffer in maintaining power balance, thereby reducing the rate of frequency change and improving the dynamic stability of the microgrid system.

Effectiveness of Predictive Control Models

The application of a predictive control model-based control strategy shows an increase in system performance in managing energy flow. This control system is able to optimize the operation of the electrolyser and fuel cell based on the predictive conditions of the system, so that energy use becomes more efficient. The simulation results show that the predictive control model is able to reduce power overshoot and improve the system's response to load changes. In addition, this strategy also improves coordination between system components, thereby strengthening the overall stability of the microgrid.

Thermodynamic Analysis and Fluid Mechanics

The results of the analysis show that hydrogen storage pressures in the medium range of 30 to 50 bar provide the most balanced performance for small-scale microgrid systems. At this range, the system still obtains adequate storage capacity without being burdened by excessive compression energy consumption. In contrast, increasing pressure to higher values does increase storage density, but it also significantly increases compression work thereby lowering overall energy efficiency. Thermodynamically, the ideal compression work of isothermal can be expressed as:

$$W_{iso} = mRT\ In\left(\frac{P_2}{P_1}\right)$$

With is the mass of hydrogen, is the specific gas constant of hydrogen, is the compression temperature, is the initial pressure, and is the final pressure. For hydrogen, used:$mRTP_1P_2$

R = 4124 J/kgK

T = 300 K

$P1$ = 1 bar

Compressive energy at 30 bar

$$W_{30} = 1 \times 4124 \times 300 \times \ln(30)$$
$$W_{30} = 4.21 \times 10^6\ \mathrm{J/kg} = 4.21\ \mathrm{MJ/kg}$$

If you take into account the compressor efficiency of 75 percent, then the actual work becomes:

$$W_{30,actual} = \frac{4.21}{0.75} = 5.61\ \mathrm{MJ/kg}$$

or equivalent to:

$$\frac{5.61}{3.6} = 1.56\ \mathrm{kWh/kg}$$

Compressive energy at 50 bar

$$W_{50} = 1 \times 4124 \times 300 \times \ln(50)$$
$$W_{50} = 4.84\ \mathrm{MJ/kg}$$

With a compressor efficiency of 75 percent:

$$W_{50,actual} = \frac{4.84}{0.75} = 6.45\ \mathrm{MJ/kg}$$

or:

$$\frac{6.45}{3.6} = 1.79\ \mathrm{kWh/kg}$$

Compressive energy at 100 bar

$$W_{100} = 1 \times 4124 \times 300 \times \ln(100)$$
$$W_{100} = 5.70\ \mathrm{MJ/kg}$$

With a compressor efficiency of 75 percent:

$$W_{100,actual} = \frac{5.70}{0.75} = 7.60\ \text{MJ/kg}$$

or:

$$\frac{7.60}{3.6} = 2.11\ \text{kWh/kg}$$

Based on these results, it can be seen that increasing pressure from 30 bar to 50 bar still provides relatively moderate additional compressive energy, which is around:

$$6.45 - 5.61 = 0.84\ \text{MJ/kg}$$

However, when the pressure is raised further to 100 bar, the additional compressive energy increases to:

$$7.60 - 6.45 = 1.15\ \text{MJ/kg}$$

This suggests that an increase in pressure above the mid-range begins to result in a greater energy penalty than the gains in storage capacity gained. In terms of volumetric capacity, the density of hydrogen can ideally be calculated using the ideal gas equation:

$$\rho = \frac{P}{RT}$$

with pressure in Pascal units. For a temperature of 300 K is obtained:

Density at 30 bar

$$\rho_{30} = \frac{3.0 \times 10^6}{4124 \times 300}$$
$$\rho_{30} = 2.43\ \text{kg/m}^3$$

Density at 50 bar

$$\rho_{50} = \frac{5.0 \times 10^6}{4124 \times 300}$$
$$\rho_{50} = 4.04\ \text{kg/m}^3$$

Density at 100 bar

$$\rho_{100} = \frac{10.0 \times 10^6}{4124 \times 300}$$
$$\rho_{100} = 8.08\ \text{kg/m}^3$$

From these results, the volume of the tank needed to store 1 kg of hydrogen can be calculated as:

$$V = \frac{m}{\rho}$$

until obtained:

at 30 bar:

$$V_{30} = \frac{1}{2.43} = 0.412\ \text{m}^3$$

at 50 bar:

$$V_{50} = \frac{1}{4.04} = 0.248\ \text{m}^3$$

At 100 bar:

$$V_{100} = \frac{1}{8.08} = 0.124\ \mathrm{m}^3$$

These results confirm that the increase in pressure does significantly reduce the volume requirement of the tank. However, in the context of a microgrid, the reduction in volume from 0.248 m^3 to 0.124 m^3 per kilogram of hydrogen when the pressure is raised from 50 bar to 100 bar must be compensated for by an increase in compression energy from 1.79 kWh/kg to 2.11 kWh/kg. Thus, for microscale systems, a pressure of 30 to 50 bar is still more rational because it provides a better compromise between compression energy requirements and storage capacity.

In terms of fluid mechanics, the flow of hydrogen from the electrolyser to the tank and from the tank to the fuel cell also shows that the pressure loss in the microgrid short pipeline is relatively small compared to the storage pressure. Using the Darcy–Weisbach approach:

$$\Delta P = f \frac{L}{D} \frac{\rho v^2}{2}$$

Suppose the pipe is used, the length of the pipe, the diameter of the pipe, the average hydrogen density, and the flow rate, then: $f = 0.02L = 5\ \mathrm{m}D = 0.01\ \mathrm{m}\rho = 3.2\ \mathrm{kg/m}^3 v = 5\ \mathrm{m/s}$

$$\Delta P = 0.02 \times \frac{5}{0.01} \times \frac{3.2 \times 5^2}{2}$$

$$\Delta P = 0.02 \times 500 \times 40$$

$$\Delta P = 400\ \mathrm{Pa}$$

or equivalent to:

$$0.004\ \mathrm{bar}$$

This value is very small compared to the operating pressure of 30 to 50 bar, so it can be concluded that pressure loss due to flow in the pipeline is not the dominant factor. The more decisive factors are the compression work and thermal conditions during the storage process.

Overall, the results of the analysis show that a storage pressure of 30 to 50 bar is the most suitable operating range for hydrogen-based microgrids. In this range, the compressive energy is still controlled in the range of 1.56 to 1.79 kWh/kg, the volumetric capacity is sufficient for the needs of small-scale systems, and the pressure loss in the hydrogen flow is relatively small. These findings confirm that medium pressure provides the best balance between thermodynamic efficiency, fluid performance, storage capacity, and operational safety.

Table 1. Comparison of Compressive Energy and Storage Characteristics of Hydrogen at Various Pressures

Pressure	**Ideal compression energy**	**Actual compression energy**	**H_2 Density**	**Volume for 1 kg H_2**
30 bar	4.21 MJ/kg	5.61 MJ/kg or 1.56 kWh/kg	2.43 kg/m³	0.412 m³
50 bar	4.84 MJ/kg	6.45 MJ/kg or 1.79 kWh/kg	4.04 kg/m³	0.248 m³
100 bar	5.70 MJ/kg	7.60 MJ/kg or 2.11 kWh/kg	8.08 kg/m³	0.124 m³

DISCUSSION

The results of the study show that the integration of the Hydrogen Energy Storage System makes a significant contribution to improving the stability of the solar–wind hybrid microgrid system, especially in reducing power fluctuations and improving frequency response. The reduction in power fluctuations of up to about 40 percent indicates that the hydrogen storage system is able to function as an effective energy buffer against the variability of renewable energy sources. These findings confirm that the mechanism of converting electrical energy into hydrogen and vice versa plays not only a storage medium, but also an active element in controlling the dynamics of the power system.

From the perspective of system dynamics, the decrease in the amplitude of power fluctuations and ramp rate indicates an improvement in the characteristics of the transient response. Systems that originally experienced sharp power changes became more muted, reducing the risk of extreme frequency deviations. This indicates that the Hydrogen Energy Storage System plays a role in increasing the effective inertia of the system, although it does not physically add to the mechanical inertia. Thus, the system becomes more stable in responding to disturbances both in terms of generation and load.

The implementation of the predictive control model also shows an important role in optimizing system performance. Predictive control capabilities in anticipating changes in operating conditions allow for more efficient regulation of energy flow between the electrolyser and fuel cell. These results show that the success of the integration of the Hydrogen Energy Storage System is not only determined by the physical characteristics of the components, but also highly dependent on the control strategy used. Without adaptive controls, the potential of storage systems cannot be optimally utilized.

In terms of thermodynamics and fluid mechanics, the results of the analysis show that storage pressure in the range of 30 to 50 bar provides the best balance between compression energy requirements and storage capacity. Calculations show that an increase in pressure above that range results in an increase in compression energy that is disproportionate to the increase in storage density. This confirms the trade-off between energy efficiency and volumetric capacity in hydrogen storage systems. In addition, fluid flow analysis shows that the pressure loss in the pipeline system is relatively small compared to the operating pressure, so it is not a major limiting factor in the system design.

When compared to a zero-storage system, the microgrids integrated with the Hydrogen Energy Storage System show a significant increase in operational reliability. The system is better able to maintain the continuity of energy supply despite fluctuations in renewable energy sources. This is particularly relevant for the southern coastal region of West Java which has the characteristics of high energy variability, so it requires an adaptive and flexible system.

However, there are some limitations in this study. The model used is still based on the assumption of ideal conditions on several components, such as the ideal gas approach to hydrogen storage and constant efficiency in electrolyzers and fuel cells. In addition, aspects of component degradation, temperature dynamics, as well as additional energy losses in real systems have not been fully modeled. Therefore, further research is needed to develop a more comprehensive model taking into account these factors.

Overall, this discussion confirmed that the integration of the Hydrogen Energy Storage System is an effective approach to improve the stability and flexibility of renewable energy-based microgrids. The combination of dynamic modeling, predictive control strategies, and optimization of operating parameters such as storage pressure is the key to achieving optimal system performance. These findings provide important implications for the development of sustainable energy systems, particularly in regions with high levels of renewable energy intermittency.

CONCLUSIONS AND RECOMMENDATIONS

This study shows that the integration of Hydrogen Energy Storage Systems in solar–wind hybrid microgrids significantly improves the stability of electric power systems. The simulation results show that power fluctuations can be reduced by about 40 percent, accompanied by a decrease in ramp rate and an increase in system frequency response. This confirms that the hydrogen storage system not only functions as an energy storage medium, but also as an active element in maintaining power balance and improving the quality of energy supply.

From an operational perspective, the application of the predictive control model has been proven to be able to optimize the coordination between the electrolyser and the fuel cell, thereby improving the efficiency of energy distribution and system response to changing conditions. In addition, thermodynamic and fluid mechanics analysis shows that storage pressures in the range of 30 to 50 bar are optimal conditions for microgrid-scale systems, as they provide a balance between energy efficiency, storage capacity, and operational safety.

Based on these results, it is recommended that the development of renewable energy-based microgrids, especially in areas with high variability of energy sources such as the southern coast of West Java, needs to consider the integration of the Hydrogen Energy Storage System as a solution to improve system stability. For further research, it is recommended to develop a more comprehensive model by considering the degradation effects of components, temperature dynamics, and experimental validation to improve the accuracy and implementation of the system under real conditions.

FURTHER STUDY

Further research is recommended to develop a more comprehensive system model by considering the effects of component degradation, temperature dynamics, and energy losses on real operational conditions. In addition, experimental validation on a laboratory scale or pilot system is required to test the reliability of the model and the results of the simulation. Further studies can also be focused on storage pressure optimization and more sophisticated adaptive control strategies to improve overall system efficiency and stability.

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