

# Comparative Performance Evaluation of Solar and Wind based Electrolysis Systems for Green Hydrogen Production

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**Abstract.** The increasing demand for sustainable energy solutions has highlighted the potential of green hydrogen as a clean energy carrier. Solar or wind-powered electrolysis systems are considered promising technologies for producing green hydrogen, yet their efficiency is limited by intermittency issues. This study evaluates the performance of solar and wind-based electrolysis systems for green hydrogen production, focusing on hydrogen production rates, energy consumption, and system stability under varying environmental conditions. The solar-powered system's hydrogen production fluctuates based on solar irradiance, with significant drops during low sunlight periods, while the wind-powered system demonstrates more stable hydrogen production due to the continuous availability of wind energy. The contribution of this paper is comparative analysis of these two renewable energy sources using MATLAB simulations. We present a simulation model for both systems and evaluate their hydrogen production under both scenarios. The results show that the wind-based system produces approximately 110 kg of hydrogen per day, while the solar system generates 80 bars of hydrogen by the end of day. These simulation results highlight the advantages of wind energy for consistent hydrogen production, while solar systems face challenges related to intermittency.

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## 1 Introduction

Renewable energy has proved to tackle the increasing challenges of climate change and also guarantees energy sustainability in long run. Among other renewable energy sources, wind and solar energy are well known as abundant sources with zero emissions during the process of production. Nevertheless, intermittency of wind and solar energy remains a major obstacle that hinders large-scale implementation of these two energy sources, especially in consistent and steady power provision [1]. Solar energy is only available during the day, and the power generated depends on weather conditions such as rain or sunshine, while wind energy systems rely heavily on variable wind speed and direction. Such inherent properties result in energy production variability.

Green hydrogen is a possible solution to help reduce the problem of the intermittency of renewable energy sources, as it can be produced through water electrolysis with renewable power. Green hydrogen itself is a clean energy carrier, since it only utilizes water and renewable electricity [2]. Hydrogen, unlike the direct usage of electrical energy, can be stored and subsequently reverted into electricity or used in industrial sectors and transportation. This enables storage of excess renewable energy produced during high-generation hours to be released during low-generation hours or when demand surpasses supply [3, 4].

A reliable solution to this problem of the inconsistency of renewable energy is integration of solar and wind energy systems in hydrogen production using the electrolysis method. Sun provides high power throughout the day, while wind energy is more available at night or when the sky is not clear, which makes these two sources complementary. Such complementarity can enable the supply of more electricity to the electrolysis process, enhancing efficiency of production and lowering total costs of hydrogen production. Moreover, hybrid solutions have been shown to decrease the cost of hydrogen, known as levelized cost of hydrogen (LCOH), and in doing so, green hydrogen becomes viable and competitive with conventional fossil-fuel-based energy production [5].

The proposed work considers a comparative technical analysis of solar and wind based green hydrogen production through electrolysis systems using MATLAB simulations. This study aims to evaluate and compare the hydrogen production potential, energy consumption, and operational stability of solar and wind-powered electrolysis systems under varying environmental conditions.

## 2 Related Works

Several studies have investigated renewable energy-powered electrolysis systems for hydrogen production. One study [6] optimized PEM water electrolyzer performance using response surface methodology, achieving significant efficiency improvements under variable power conditions. That work established

baseline performance metrics for PEM electrolyzers operating with fluctuating renewable inputs. While the techno-economic analysis provided valuable insights, it lacked a detailed performance comparison between different renewable energy sources for hydrogen production. Wind-powered electrolysis systems have received limited comparative attention in recent literature. Another study [7] examined solid oxide electrolysis technology for power-to-gas applications, focusing on high-temperature operation advantages. That work concentrated on SOE technology rather than comparative performance evaluation of renewable energy sources.

Hybrid renewable systems have been proposed as solutions to intermittency issues. Research [8] developed advanced MPPT algorithms for PV systems under partial shading, demonstrating 15% performance improvements during variable solar conditions. However, the study did not directly evaluate the impact on hydrogen production rates or provide a comparative analysis with other renewable sources. Large-scale hydrogen production economics were analyzed in [9], which found that facilities producing over 100 kg/day achieve better cost-effectiveness through economies of scale. Feasibility studies of combined solar-wind systems were reported in [10], identifying integration challenges but not providing detailed production rate comparisons. Similarly, [11] analyzed energy management strategies in hydrogen microgrids without quantitative comparison of individual renewable sources.

System optimization approaches have been explored through various methodologies. For example, [12] developed integration strategies for renewable energy with hydrogen storage, focusing on design optimization rather than comparative performance analysis. A review [13] of hydrogen storage technologies in microgrids did not address production rate differences between solar and wind systems. Recent technological advances in electrolysis have been documented in [14], which examined high-efficiency PEM systems with advanced catalysts and membranes. A comprehensive review [15] of electrolyzer technologies emphasized modeling approaches for sustainable applications. Both studies focused on electrolyzer technology rather than renewable energy source comparison.

Smart grid integration research has also emerged as a growing field. For example, [16] analyzed hydrogen integration pathways in smart grids, while [17] investigated campus microgrid applications. These studies addressed grid integration aspects without detailed comparative investigation of renewable source for production of hydrogen. In [18], performance analysis of wind-powered electrolysis systems were examined combined with energy storage for production of green hydrogen. A study [19] investigated mobile hydrogen supply systems for microgrids resilience. Both works focused on application-specific implementations rather than the fundamental comparison of renewable energy sources.

Recent optimization techniques have been used to solar systems specifically. For example, [20] discussed the technical and economic feasibility valuation of hybrid energy systems for hydrogen generation and electricity.

A significant gap exists in the literature regarding direct performance comparison between solar- and wind-powered electrolysis systems. Most existing studies focus on individual technologies or specific applications without providing quantitative comparative analysis of hydrogen production rates, system stability, and energy consumption under varying environmental conditions. This gap motivates the present comparative study using MATLAB simulations to evaluate both systems under similar operational parameters and provide direct performance metrics for green hydrogen production using wind and solar sources.

### 3 Methodology

#### 3.1 Hydrogen Electrolyzer

Hydrogen electrolysis is a electrochemical process to split water into oxygen and hydrogen by using electricity, as shown in Fig. 1. It has become a foundation of renewable energy system, particularly when paired with energy generators such as photovoltaics to produce green hydrogen. These systems can work with hydrogen-based energy storage, where surplus renewable energy is utilized to produce hydrogen gas, which can then be stored and in future re-converted into electrical power by fuel cells on demand.

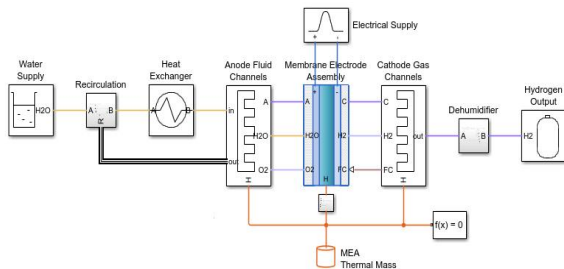


Fig. 1. Hydrogen electrolyzer [21]

The frequently used electrolyzers for hydrogen production are alkaline, solid oxide and polymer electrolyte membrane (PEM) types. PEM electrolyzers are especially well-suited for pairing with renewable energy sources, such as solar resources, since they can operate efficiently across a range of power inputs. In these systems, water is fed into electrolyzer at anode side, where it is oxidized to oxygen, electrons, and protons. The protons diffuse through a semipermeable membrane, while electrons flow via external circuit to cathode, where they react with the protons to yield hydrogen.

In a solar-driven hydrogen production system, PV panels provide energy to the electrolyzer. The solar array power output can be determined from the efficiency, panel area, and solar irradiance, as described in Eq. 1:

$$P_{solar} = A \cdot G \cdot \eta_{panel} \quad (1)$$

Where  $A$  = area of solar panels ( $m^2$ )  $G$  = solar irradiance ( $W/m^2$ )  $\eta_{panel}$  = efficiency of solar panels.

In a wind-driven hydrogen production system, the power output of the wind turbine supplies energy to the electrolyzer. The available wind power can be estimated from the turbine's rated capacity, wind speed, and efficiency, as given in Eq. 2.

$$P_{wind} = \frac{1}{2} \rho A \cdot C_p \cdot v^3 \eta_{turbine} \quad (2)$$

where  $\rho$  is the air density ( $kg/m^3$ ),  $A$  is the swept area of the turbine blades ( $m^2$ ),  $C_p$  is the power coefficient (efficiency of the turbine),  $v$  is the wind speed ( $m/s$ ),  $\eta_{turbine}$  is the mechanical and electrical efficiency of the system.

This power is then balanced with the electrolyzer's energy consumption, which can be modeled using Eq. 3.

$$P_{Electrolyzer} = \frac{E_{required}}{Operating Time} \quad (3)$$

Where  $E_{required}$  is the energy required to produce the hydrogen gas, and  $t$  depends on solar energy available and the efficiency of electrolyzer. The process of connecting the solar power input to electrolyzer power demand then allows us to simulate the hydrogen production system performance through the day, where solar availability varies.

### 4 Results & Discussion

#### 4.1 Solar-Powered Hydrogen Production System

The current study investigates the performance of a solar-powered electrolysis system designed for green hydrogen production. This system is powered exclusively with solar energy as shown in Fig. 2.

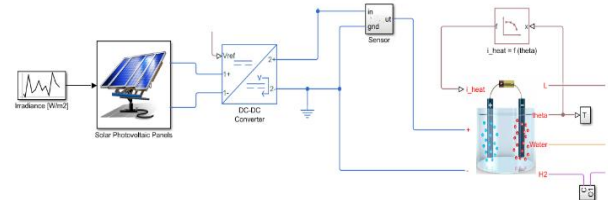
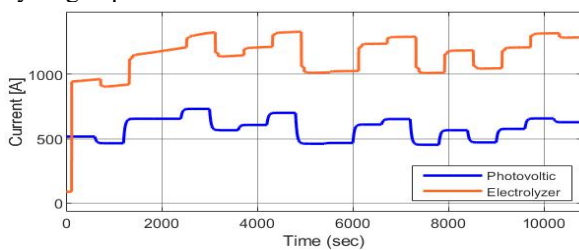


Fig. 2. Solar Powered Hydrogen Production System

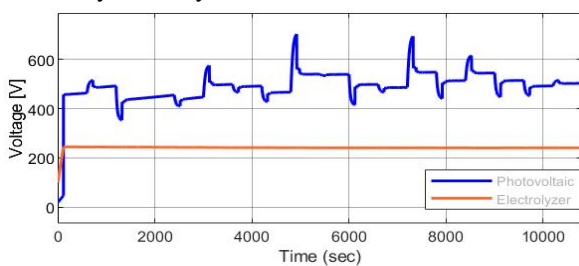
The analysis provides a comprehensive overview of system's operation under changing solar irradiance conditions. The findings presented below underscore the relationship among solar power generation and hydrogen production, emphasizing both the system's potential and challenges posed by intermittency of solar power. The simulation results clearly indicate a direct correlation between solar power generation and hydrogen production. As anticipated, hydrogen production follows the pattern of solar irradiance, with increases in solar energy input leading to a proportional rise in hydrogen output. When solar irradiance is strong, the electrolyzer receives sufficient power to produce hydrogen in large quantities. Conversely, when solar irradiance is lower (e.g., due to clouds, weather, or at night), the electrolyzer reduces or stops hydrogen production. This behavior demonstrates the intermittency of solar power and its effect on hydrogen production.

Another key finding is the impact of fluctuating solar energy availability, which shows that hydrogen generation can be occasional. The operation of the electrolyzer depends on solar irradiance; therefore, hydrogen production may be affected by variability in the energy input. When solar irradiance is weak, the energy supplied to the electrolyzer decreases, resulting in reduced hydrogen production. The periodic pattern shown in Fig. 3 indicates that the system is sensitive to environmental changes and dependent on solar energy. During sunny days, the current in the electrolyzer may decrease, limiting hydrogen generation. This variation in current is typical of solar-powered systems, as the electrolyzer cannot continuously and steadily generate hydrogen without a consistent energy source. Consequently, the instability of the solar energy input presents a major challenge to ensuring constant hydrogen production.



**Fig. 3.** Current for Electrolyzer and Photovoltaic

The analysis also indicates that energy dynamics play an essential role in the system. An increase in energy consumption is observed with increasing hydrogen production, reflecting the efficiency of the system in converting solar power into hydrogen. However, when solar irradiance is very high, the photovoltaic panels produce more power than is necessary. This excess energy is not utilized for hydrogen production, leading to lost opportunities. In the absence of a viable energy storage system, even the surplus solar energy produced at peak times remains unutilized, reducing the overall efficiency of the system.

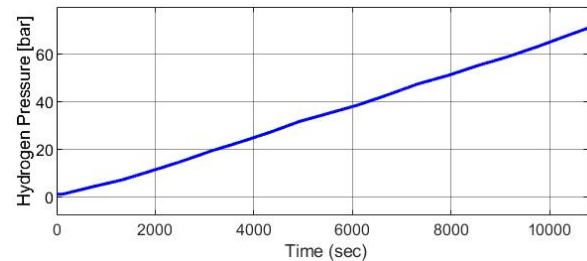


**Fig. 4.** Voltage for Electrolyzer and Photovoltaic

This relationship is shown in Fig. 4, where voltage fluctuations correspond to varying energy consumption patterns of the electrolyzer. When solar irradiance is high, the system consumes more energy, and the voltage rises. Conversely, when irradiance is lower, energy consumption decreases, resulting in a drop in voltage and, consequently, a reduction in hydrogen production. Based on these energy consumption and voltage fluctuations, total hydrogen production was estimated. These observations suggest that a mechanism should be developed to store surplus solar energy during high irradiance periods and supply it

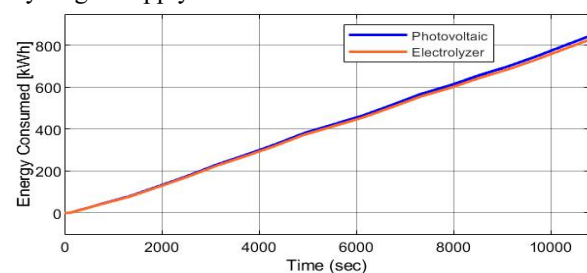
when irradiance is low, thereby maximizing overall hydrogen production.

Although the solar electrolysis system does not operate constantly, the findings show that solar power can effectively produce hydrogen under favorable solar conditions. Fig. 5 demonstrates that hydrogen pressure increases with higher solar energy, indicating efficient system operation during optimal conditions.



**Fig. 5.** Hydrogen Pressure

This finding is further validated by Fig. 6 which shows a positive relationship between energy consumption and hydrogen production, with an estimated 80 bar of hydrogen produced per day under favorable conditions. The photovoltaic panels and the electrolyzer simultaneously require more energy to produce more hydrogen, meaning that the system consumes significantly more energy when solar energy is abundant. The energy demand of the electrolyzer is closely correlated with the available solar energy, indicating that the system performs best under optimal solar conditions. While the solar-powered electrolysis system can generate hydrogen effectively during periods of high solar irradiance, its primary constraint is the intermittency of solar power. Hydrogen generation depends strictly on the supply of solar energy, and low irradiance conditions reduce or stop production. This intermittency remains a major challenge for ensuring a continuous and steady hydrogen supply.

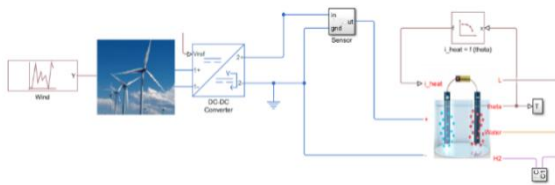


**Fig. 6.** Consumed Energy

To overcome this limitation, the integration of energy storage mechanisms capable of accommodating surplus energy generated during high solar irradiance period is essential. Energy storage systems would allow the system to utilize excess energy during periods of low solar irradiance, thereby reducing the effects of intermittent solar power. These mechanisms could include batteries or hydrogen storage solutions. Additionally, energy storage helps minimize the opportunity loss associated with unused excess energy, resulting in a more efficient and reliable system overall.

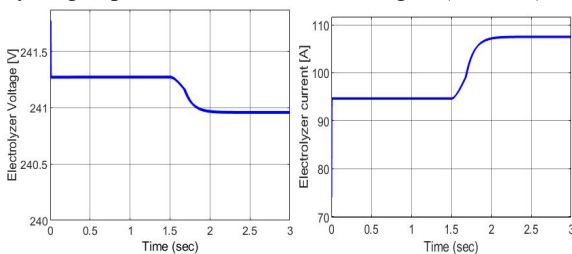
## 4.2 Wind-Powered Hydrogen Production System

The presented system integrates a wind turbine with a DC-DC converter and an electrolyzer for green hydrogen production. The wind turbine converts wind energy into electrical power, which is regulated by the DC-DC converter to provide a stable voltage suitable for electrolysis. Sensors monitor key electrical parameters, ensuring that power delivered to electrolyzer remains consistent despite the variability of wind energy. This controlled power supply is important for maintaining efficiency and operational stability of electrolyzer, which facilitates water-splitting reaction to generate hydrogen gas. The system design addresses both the electrical and thermal dynamics of hydrogen production, demonstrating feasibility of using wind power as a reliable renewable source. Overall, the results indicate that coupling wind power with a DC-DC converter and sensor feedback can optimize electrolysis processes, contributing to sustainable and efficient production of green hydrogen, as shown in Fig. 7.



**Fig. 7.** Wind-Powered Hydrogen Production System

The results show that the electrolyzer voltage initially remains stable at around 241.35 volts, indicating steady hydrogen production under constant electrical input. After 1.5 seconds, the voltage drops slightly to 241 volts, reflecting enhanced efficiency as the wind power input increases. This reduction demonstrates the electrolyzer's ability to operate effectively with less electrical energy due to improved power availability. The generator phase voltage oscillates around 250 volts, with transient fluctuations causing voltage spikes near 600 volts and dips below -400 volts. After 1.5 seconds, the voltage stabilizes near 350 volts, showing adaptation to increased wind energy and a higher steady operating point, which supports greater hydrogen production, as shown in Fig. 8 (left side).

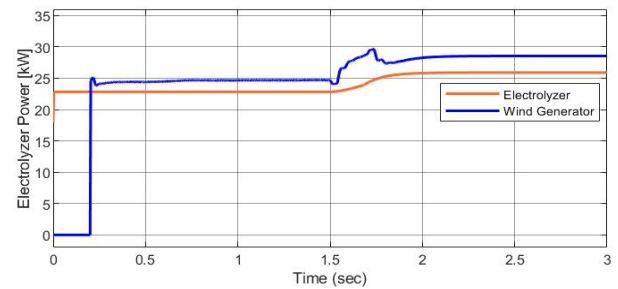


**Fig. 8.** Voltage and Current for Electrolyzer

The electrolyzer current begins at 97 A and remains steady for the first 1.2 seconds, before rising sharply to 107 A by 2 seconds, reflecting an increase in power input due to improved wind conditions or system adjustments. The generator current begins at  $\pm 100$  A and exhibits dynamic behavior with changes in wind

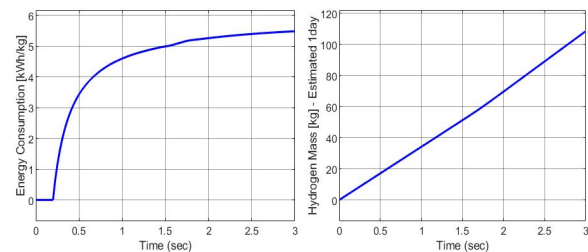
speed. After 1.5 seconds, the current waveform stabilizes, confirming that the system has adjusted to the new operating conditions and is producing hydrogen in a stable and efficient manner, as indicated in Fig. 8 (right side).

Fig. 9 shows the dynamic relationship among the power output of wind generator and power consumption of electrolyzer when the system operates over a three-hour interval. Initially, the wind generator rapidly increases its power output, which then stabilizes around 1.5 hours as the power reaches a peak of approximately 24 kW. The output power eventually reaches a maximum of 30 kW and tends to stabilize at around 29 kW, influenced by natural variations in wind speed. Comparatively, the power consumption of the electrolyzer increases gradually, starting at 23 kW and rising to nearly 26 kW after 1.5 hours before leveling off. The electrolyzer's power intake depends on the available wind power but exhibits smoother behavior, likely due to operational constraints or energy management strategies that ensure steady hydrogen production. This pattern demonstrates that the system can adjust in real time and maximize hydrogen production with the available wind energy, highlighting the benefits of integrating wind energy with electrolysis for green hydrogen generation.



**Fig. 9.** Power Consumption

Fig. 10 illustrates two important aspects of the wind-powered hydrogen production system: energy consumption per kilogram of produced hydrogen and estimated mass of hydrogen produced over a single day. The graph in Fig. 10 (left) shows that energy consumption increases sharply at the beginning, reflecting the initial energy required to start the system and initiate electrolysis. After this phase, consumption levels off slightly above 6 kWh/kg, indicating efficient use of energy through continuous hydrogen production.



**Fig. 10.** Hydrogen pressure and consumed energy

The plot in Fig. 10 (right) shows the estimated mass of hydrogen produced, exhibiting a nearly linear increase from 0 kg to approximately 110 kg over 24 hours. This linear output indicates a steady conversion of wind energy into hydrogen, demonstrating uninterrupted and consistent hydrogen production using only wind as the power source.

### 4.3 Comparison of Solar and Wind based Green Hydrogen Production

The comparative analysis of wind and solar based electrolysis system for production of green hydrogen provides valuable insights into their relative efficiencies and hydrogen output capabilities. Both systems utilize renewable energy to operate the electrolysis process that splits water into oxygen and hydrogen, making green hydrogen as clean energy alternative.

Hydrogen production in solar-powered electrolysis system is directly related to solar irradiance, varying with the availability of sunlight. The system operates efficiently on sunny days, when irradiance is high, resulting in a higher rate of hydrogen production. Under low solar irradiance conditions such as cloudy weather or at night hydrogen production is reduced or stops entirely. The system's performance can be improved by integrating an energy storage mechanism, which would store surplus solar energy throughout peak sunlight hours and supply it when solar energy is unavailable, thereby providing more stable hydrogen output.

In contrast, the wind-based electrolysis system offers a more consistent rate of hydrogen production. Wind energy can be harnessed both day and night, although production depends on fluctuations in wind speed. The system generates more hydrogen during periods of high wind speed and less during calm periods. Energy management strategies can be applied to optimize electrolyzer operation in response to changing wind conditions; however, some variability may still occur depending on local wind patterns. Wind-driven electrolysis is generally more reliable for continuous hydrogen production, achieving peak values of approximately 110 kg per day under steady wind conditions. Although solar-powered systems are effective during daytime, they experience variability in production, with hydrogen pressure reaching around 80 bar by the end of the day. Therefore, wind-based systems typically produce more hydrogen daily due to their more continuous power availability.

## 5 Conclusion

In conclusion, this study demonstrates that both solar- and wind-based electrolysis systems are effective for green hydrogen production, with wind-powered systems providing more stable and continuous output. The findings have several practical implications: wind-based systems offer more reliable daily hydrogen production, which may improve scalability for industrial applications, while solar systems, despite intermittency, can still contribute effectively when combined with energy storage. Integrating energy storage solutions or hybridizing solar and wind systems could further enhance system efficiency and mitigate variability, making green hydrogen production further economically feasible and adaptable to policy targets for renewable energy adoption. Future work should explore the techno-economic feasibility of hybrid systems, optimal energy storage strategies, and policy-

driven deployment scenarios to maximize green hydrogen production while ensuring cost-effectiveness and grid integration.

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