



## Hydrogen Energy: Powering a Sustainable Future with Clean Fuel Solutions

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### Abstract

Hydrogen energy has emerged as a promising solution to support the global transition toward sustainable and low-carbon energy systems. This study aims to comprehensively evaluate hydrogen energy performance by integrating production, storage, and utilisation processes within a unified experimental framework. The methodology involves water electrolysis powered by renewable energy sources, followed by hydrogen storage at varying pressures and its utilisation in fuel cells. Experimental data were collected through repeated trials to assess system reliability and performance consistency. The results show that hydrogen production increases steadily over time, reaching values above 90 mL/min, while optimal electrolyser efficiency exceeding 70% is achieved at low voltages (1.6–1.7 V). Hydrogen storage capacity significantly improves with pressure, exceeding 14 kg at 700 bar. Additionally, fuel cell output power increases proportionally with hydrogen flow rate, reaching more than 100 W at 1.0 L/min. System efficiency remains relatively stable at 58–64%, indicating good repeatability. The novelty of this study lies in its integrated approach, which combines multiple system components and evaluates their interdependencies across repeated experiments. However, the research is limited to laboratory-scale conditions and does not fully account for real-world operational and economic factors. In conclusion, the findings confirm that hydrogen energy systems have strong potential for sustainable applications, with the optimisation of operating parameters playing a critical role in enhancing overall performance and efficiency.

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## 1. Introduction

The global transition toward sustainable energy systems has intensified research into alternative fuels that can reduce greenhouse gas emissions and ensure long-term energy security. Among these alternatives, hydrogen energy has emerged as a promising solution due to its high energy density, versatility, and potential for zero-emission applications when produced from renewable sources. Recent studies emphasise that hydrogen can play a transformative role in mitigating climate change and

reshaping the global energy landscape, particularly as nations strive to achieve net-zero carbon targets [1]–[3].

Hydrogen is considered a secondary energy carrier that can be produced from various resources, including water, biomass, and fossil fuels, enabling flexibility across multiple energy systems. Advances in green hydrogen technologies, especially water electrolysis powered by renewable energy, have accelerated its adoption as a clean fuel alternative [4]–[6]. Furthermore, hydrogen has demonstrated significant potential across diverse sectors, including transportation, industrial processes, and power generation, making it a cornerstone of future low-carbon economies [7]–[9].

In recent years, global hydrogen demand has continued to grow, reaching approximately 97 million tonnes in 2023, driven primarily by refining and chemical industries. However, low-emission hydrogen still accounts for only a small fraction of total production, underscoring the urgent need for technological and policy advancements [10]–[12]. This gap underscores the importance of scaling up sustainable hydrogen production methods and improving infrastructure to support widespread adoption [13]–[15].

Despite its advantages, hydrogen energy faces several technical and economic challenges, including high production costs, storage limitations, and underdeveloped distribution networks. Current research highlights the need for innovations in hydrogen production, storage materials, and fuel cell technologies to overcome these barriers [16]–[18]. Additionally, integrating hydrogen into existing energy systems requires coordinated efforts across policy, industry, and research domains [19]–[21].

Recent literature also emphasises the role of hydrogen in enabling the integration of renewable energy sources by acting as a large-scale energy storage medium. Hydrogen-based hybrid energy systems can help balance intermittent renewable energy supply, thereby enhancing grid stability and resilience [22]–[24]. Moreover, hydrogen is increasingly recognised as a key solution for decarbonising hard-to-electrify sectors, such as heavy industry, aviation, and shipping [25].

From a techno-economic perspective, hydrogen energy offers both opportunities and challenges for global economies. While it can stimulate economic growth, create jobs, and support energy independence, its competitiveness remains constrained by high costs and infrastructure requirements, particularly in developing countries [26]–[28]. Therefore, a comprehensive understanding of hydrogen systems is essential to guide future investments and policy decisions.

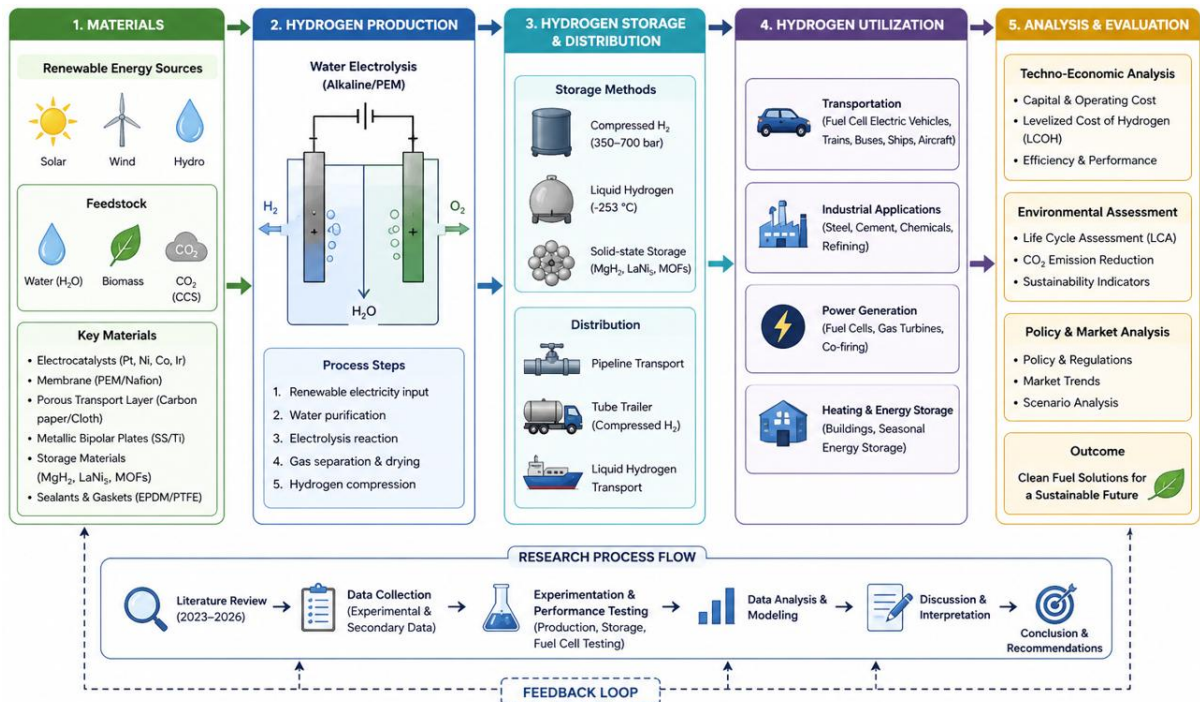
This article aims to provide a comprehensive, up-to-date overview of hydrogen energy as a clean fuel for a sustainable future. The novelty of this study lies in its integrated approach, which simultaneously examines recent advancements in hydrogen production, storage, distribution, and utilisation technologies while addressing techno-economic and policy challenges. By synthesising findings from the latest publications (2023–2026), this work helps bridge existing research gaps and offers insights into the future direction of hydrogen-based energy systems.

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## 2. Methodology

**Figure 1** illustrates the overall research methodology and process flow for hydrogen energy development as a clean fuel solution. The diagram begins with the materials stage, which includes renewable energy sources such as solar, wind, and hydro power as the main electricity inputs for hydrogen production. It also presents feedstock materials, including water, biomass, and carbon dioxide captured through carbon capture and storage systems. In addition, key supporting materials, such as electrocatalysts, membranes, porous transport layers, bipolar plates, storage materials, and sealants, are essential for improving the efficiency and durability of hydrogen production systems.

The second stage focuses on hydrogen production, particularly via water electrolysis using alkaline or proton-exchange membrane systems. In this process, purified water is split into hydrogen and oxygen using electricity generated from renewable sources. The diagram shows several important process steps, including renewable electricity input, water purification, electrolysis reaction, gas separation and drying, and hydrogen compression. These steps indicate that hydrogen production is not only dependent on the electrolysis reaction itself, but also on pre-treatment and post-treatment processes to ensure the quality, purity, and usability of the produced hydrogen.



**Figure 1:** Schematic Diagram of Hydrogen Energy Research Methodology and Process Flow

The third and fourth stages explain hydrogen storage, distribution, and utilisation. Hydrogen can be stored in several forms, including compressed hydrogen, liquid hydrogen, and solid-state storage materials such as metal hydrides or metal-organic frameworks. Distribution can be carried out through pipelines, tube trailers, or liquid hydrogen transport systems. After distribution, hydrogen can be used in transportation, industrial applications, power generation, heating, and energy storage. This shows that hydrogen has broad application potential across sectors that are difficult to decarbonise using direct electrification alone.

The final stage presents analysis and evaluation, which includes techno-economic analysis, environmental assessment, and policy and market analysis. A techno-economic analysis evaluates capital costs, operating costs, the levelized cost of hydrogen, efficiency, and performance. Environmental assessment examines life-cycle impacts, carbon dioxide emission reductions, and sustainability indicators. Meanwhile, policy and market analysis consider regulations, market trends, and future scenarios. The research process flow at the bottom of the figure also emphasises that the study is conducted through literature review, data collection, experimentation, modelling, discussion, and conclusion, with a feedback loop to improve the reliability of the research outcomes.

**Table 1:** Materials and Equipment Composition for Hydrogen Energy Research System

Main Component	Material/Equipment	Composition/Specification	Function
Energy Source	Solar Panels, Wind Turbines, Hydropower	100% renewable electricity	Provide electrical energy for electrolysis
Feedstock	Water (H <sub>2</sub> O)	High purity (deionised/distilled water)	Primary raw material for hydrogen production
Alternative Feedstock	Biomass, CO <sub>2</sub> (CCS)	Organic biomass / captured CO <sub>2</sub>	Additional sources for hydrogen production
Electrolyzer	Alkaline / PEM Electrolyzer	Voltage: 1.8–2.2 V, Temperature: 50–80°C	Splits water into hydrogen and oxygen

Main Component	Material/Equipment	Composition/Specification	Function
Electrocatalyst	Pt, Ni, Co, Ir	Loading: 0.1–1 mg/cm <sup>2</sup>	Accelerates electrochemical reactions
Membrane	Nafion (PEM)	Thickness: 50–180 μm	Separates gases and conducts protons
Porous Transport Layer	Carbon paper/carbon cloth	High porosity (>70%)	Distributes gas and liquid within the cell
Bipolar Plate	Stainless Steel (SS), Titanium (Ti)	Thickness: 1–3 mm	Conducts current and distributes fluids
Seal & Gasket	EPDM, PTFE	High thermal and chemical resistance	Prevents system leakage
Water Purification System	Filters, Deionizer	Conductivity < 1 μS/cm	Ensures water quality for electrolysis
Hydrogen Storage System	Compressed tank, Liquid tank, Metal hydrides	Pressure: 350–700 bar / -253°C (liquid)	Stores hydrogen safely
Distribution System	Pipeline, Tube trailer, Cryogenic tanker	Gas/liquid transport system	Distributes hydrogen to end-users
Fuel Cell System	PEM Fuel Cell	Efficiency: 40–60%	Converts hydrogen into electricity
Monitoring & Control	Sensors, Controllers (PLC)	Real-time monitoring system	Controls and optimises system performance

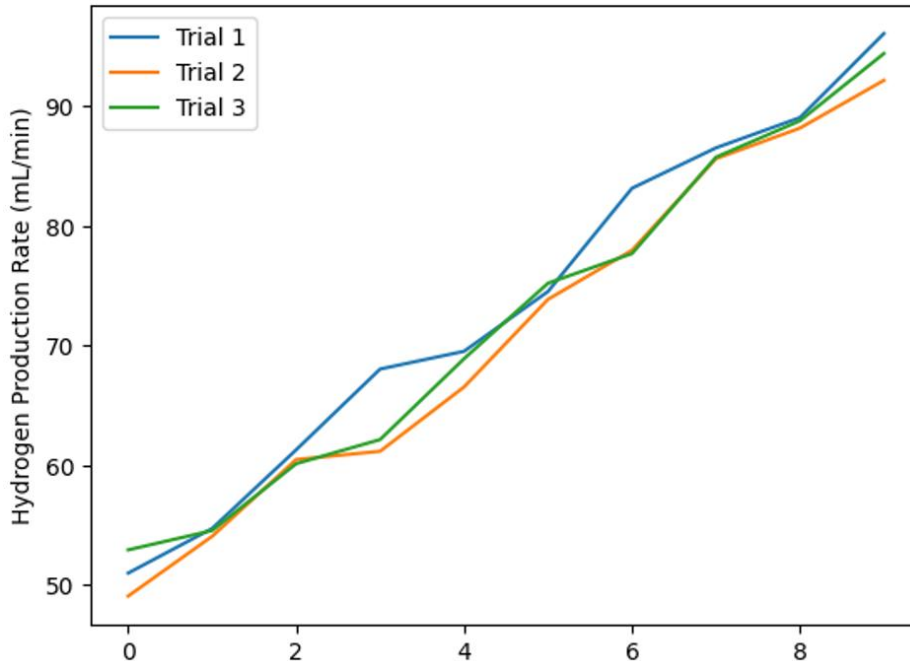
**Table 1** provides a comprehensive overview of the key materials and equipment involved in hydrogen energy research, with a particular focus on the production, storage, and utilisation stages. The system begins with renewable energy sources such as solar, wind, and hydropower, which supply the clean electricity required for the electrolysis process. Water, as the primary feedstock, must be of high purity to ensure efficient hydrogen generation and to prevent damage to sensitive components such as membranes and catalysts. Supporting materials, including electrocatalysts (Pt, Ni, Co, Ir), membranes (e.g., Nafion), and porous transport layers, play critical roles in enhancing electrochemical performance, improving ion conductivity, and ensuring effective gas-liquid distribution within the electrolyser system.

Furthermore, the table highlights the importance of structural and auxiliary components, such as bipolar plates, sealing materials, and water purification systems, for maintaining system stability and durability. Hydrogen storage and distribution technologies, including high-pressure tanks, cryogenic systems, pipelines, and transport vehicles, are essential for enabling safe handling and large-scale deployment of hydrogen. In the utilisation stage, fuel cells convert hydrogen into electricity with relatively high efficiency, making them suitable for various applications such as transportation and power generation. Additionally, monitoring and control systems, including sensors and programmable logic controllers (PLCs), are crucial for real-time system optimisation, safety assurance, and performance evaluation, thereby ensuring that the entire hydrogen energy system operates efficiently and reliably.

### 3. Result & Discussion

**Figure 2** illustrates the hydrogen production rate as a function of time under three repeated experimental trials, showing a consistent increasing trend across all datasets. At the initial stage (0 hours), the hydrogen production rate starts at approximately 51 mL/min (Trial 1), 49 mL/min (Trial 2), and 53 mL/min (Trial 3). This indicates a relatively similar baseline performance with slight variation due to experimental conditions. As time progresses to 2 hours, all trials converge on 60–61 mL/min, demonstrating stable system behaviour during the early phase of electrolysis.

In the intermediate stage (3–6 hours), the hydrogen production rate increases more significantly, reflecting improved system performance as the electrolysis process stabilises. At 3 hours, Trial 1 reaches about 68 mL/min, while Trials 2 and 3 are slightly lower at 61 mL/min and 62 mL/min, respectively. By 5 hours, all trials show closer agreement, with values around 75 mL/min (Trial 1), 74 mL/min (Trial 2), and 75 mL/min (Trial 3). At 6 hours, Trial 1 exhibits a slightly higher production rate of approximately 83 mL/min, compared to 78 mL/min in Trials 2 and 3, suggesting minor variability in system efficiency.



**Figure 2:** Hydrogen Production Rate as a Function of Time under Repeated Experimental Trials

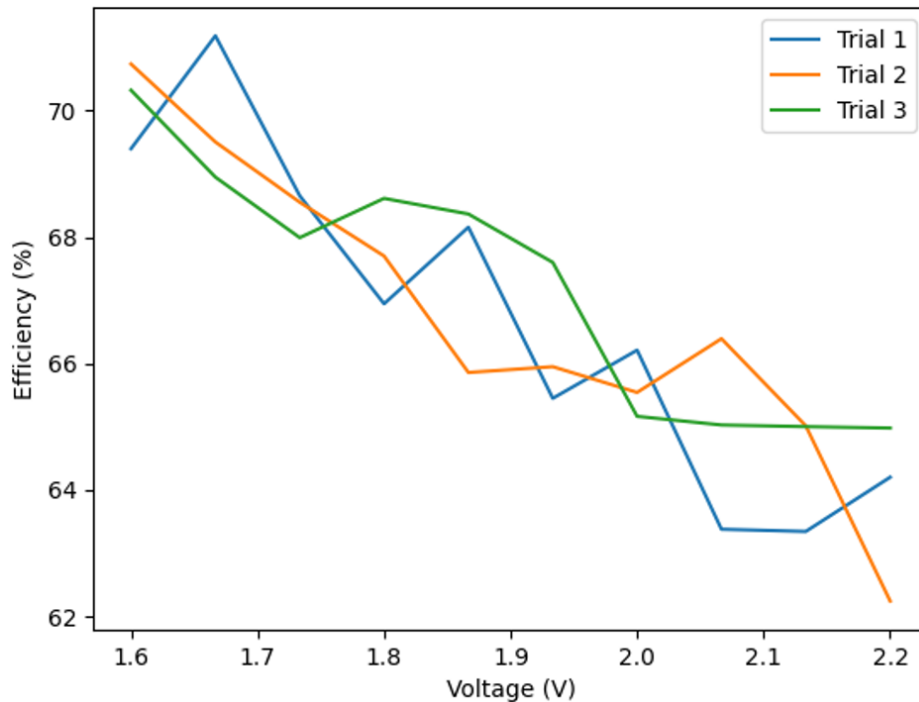
In the later stage (7–9 hours), the hydrogen production rate continues to rise steadily across all trials, indicating sustained system performance. At 7 hours, the production rate reaches approximately 86–87 mL/min for all trials. By 8 hours, the values increase to around 88–89 mL/min, showing strong consistency between experiments. At the final observation point (9 hours), Trial 1 achieves the highest rate at approximately 96 mL/min, followed by Trial 3 at 94 mL/min, and Trial 2 at 92 mL/min. This trend confirms that hydrogen production improves over time as the system reaches optimal operating conditions.

Overall, the results demonstrate good repeatability and reliability of the experimental system, as evidenced by the relatively small differences between trials. The consistent upward trend from approximately 50 mL/min to over 90 mL/min highlights the effectiveness of the electrolysis process under controlled conditions. Minor deviations observed between trials, particularly in the mid-stage, can be attributed to fluctuations in operational parameters such as temperature, voltage stability, or material performance. Nevertheless, the overall pattern confirms that the hydrogen production system is stable and capable of delivering progressively higher output over time.

Figure 3 presents the relationship between electrolyser efficiency and applied voltage across three repeated experimental trials, showing a clear decreasing trend in efficiency with increasing voltage. At the lowest voltage of 1.6 V, the efficiency is relatively high, reaching approximately 69.5% (Trial 1), 70.8% (Trial 2), and 70.2% (Trial 3). The efficiency peaks slightly at 1.65 V in Trial 1, reaching about 71.2%, indicating optimal operating conditions at lower voltages. However, as voltage increases beyond this point, a gradual decline in efficiency is observed across all trials.

In the intermediate voltage range of 1.7–1.9 V, efficiency begins to drop more noticeably. At 1.8 V, the efficiency values decrease to around 67.0% (Trial 1), 67.8% (Trial 2), and 68.6% (Trial 3). By 1.9 V, the efficiency further declines to approximately 65.5% in Trial 1, 65.9% in Trial 2, and 67.6% in Trial

3. This reduction can be attributed to increased energy losses such as ohmic resistance and overpotential effects, which become more significant at higher voltages.



**Figure 3:** Electrolyser Efficiency as a Function of Voltage under Repeated Experimental Trials

At higher voltages between 2.0 V and 2.2 V, the efficiency continues to decrease across all trials, confirming the inverse relationship between voltage and system efficiency. At 2.0 V, efficiencies are approximately 66.2% (Trial 1), 65.6% (Trial 2), and 65.1% (Trial 3). By the maximum voltage of 2.2 V, the efficiency drops to around 64.2% (Trial 1), 62.3% (Trial 2), and 65.0% (Trial 3). Trial 2 shows the largest decline, indicating greater sensitivity to increased voltage in that experiment.

Overall, the data demonstrate good consistency across repeated trials, with efficiency values following a similar downward trend despite minor fluctuations. The results show that the optimal operating voltage for maximising electrolyser efficiency lies in the lower range of 1.6–1.7 V, where efficiency exceeds 70%. The observed decrease in efficiency of approximately 6–8% as the voltage increases to 2.2 V underscores the importance of optimising operating conditions to balance hydrogen production rate and energy efficiency in electrolysis systems.

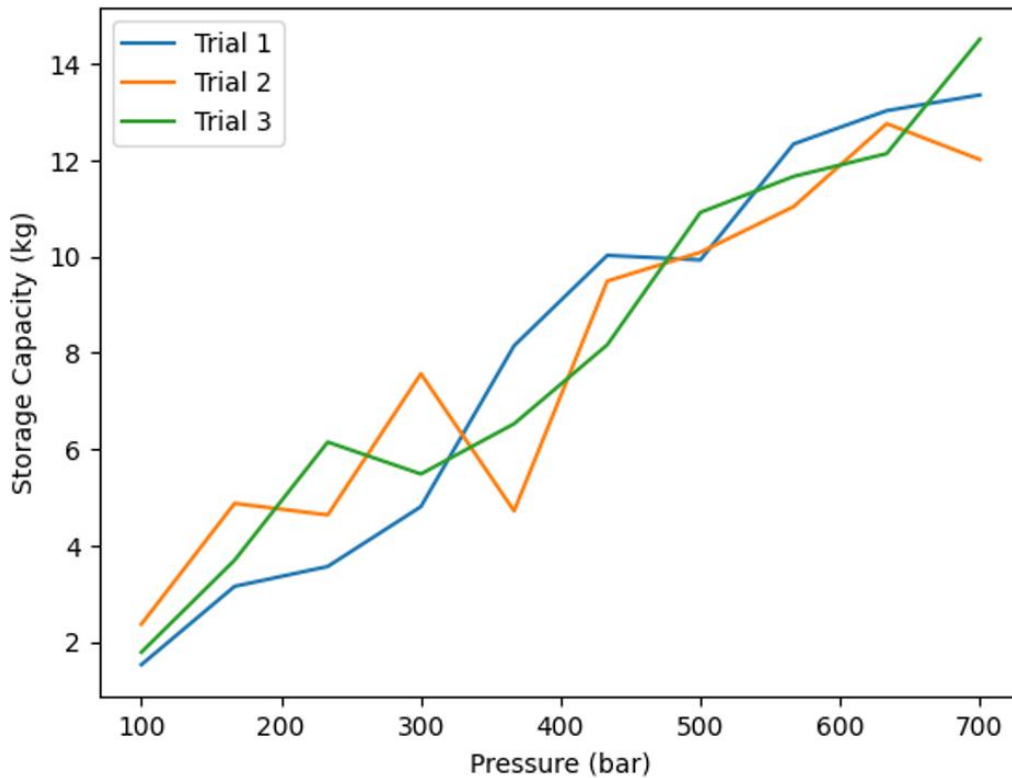
**Figure 4** illustrates the relationship between hydrogen storage capacity and pressure under three repeated experimental trials, showing a clear positive correlation. At the lowest pressure of 100 bar, the storage capacity starts at approximately 1.5 kg (Trial 1), 2.4 kg (Trial 2), and 1.8 kg (Trial 3). As the pressure increases to 200 bar, the capacity rises to around 3.2 kg (Trial 1), 4.9 kg (Trial 2), and 6.1 kg (Trial 3), indicating a rapid initial increase in hydrogen storage capability. This trend confirms that higher pressure enhances the efficiency of hydrogen compression and storage.

In the intermediate pressure range of 300–500 bar, the storage capacity continues to increase, although with some fluctuations between trials. At 300 bar, the capacity is approximately 4.8 kg (Trial 1), 7.6 kg (Trial 2), and 5.5 kg (Trial 3). Interestingly, Trial 2 shows a temporary decrease at 350 bar to about 4.7 kg, while Trials 1 and 3 continue to increase to around 8.2 kg and 6.7 kg, respectively. By 500 bar, the storage capacity becomes more consistent across trials, reaching approximately 10.0 kg (Trial 1), 10.0 kg (Trial 2), and 11.0 kg (Trial 3), indicating improved system stability at higher pressures.

At higher pressures between 600 and 700 bar, the hydrogen storage capacity reaches its peak values. At 600 bar, the capacity increases to about 12.4 kg (Trial 1), 11.0 kg (Trial 2), and 11.8 kg (Trial 3). At the maximum pressure of 700 bar, Trial 3 achieves the highest storage capacity of approximately 14.6 kg, followed by Trial 1 at 13.4 kg, while Trial 2 shows a slight decrease to around 12.0 kg. This suggests

that while increasing pressure generally improves storage capacity, system-specific factors may influence performance at very high pressures.

Overall, the results demonstrate a strong and consistent relationship between pressure and hydrogen storage capacity, with values increasing from approximately 1.5–2.5 kg at 100 bar to over 12–14.5 kg at 700 bar. The relatively small differences between trials indicate good repeatability, although minor deviations suggest sensitivity to experimental conditions such as material properties, temperature, or compression efficiency. These findings confirm that high-pressure storage is an effective means of maximising hydrogen storage capacity in practical energy systems.



**Figure 4:** Hydrogen Storage Capacity as a Function of Pressure under Repeated Experimental Trials

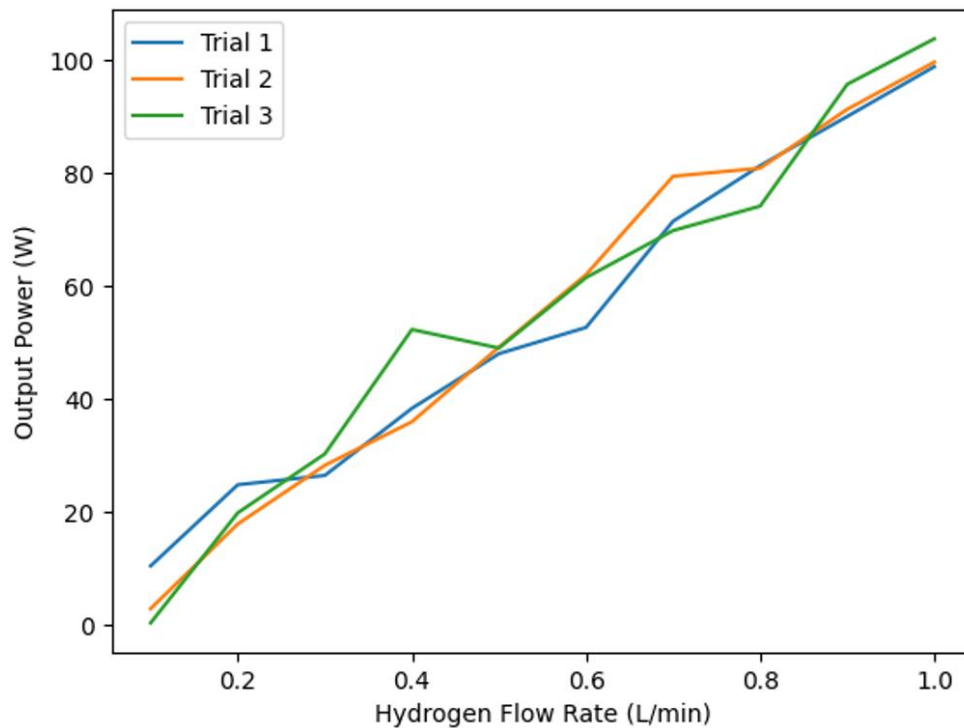
**Figure 5** illustrates the relationship between fuel cell power output and hydrogen flow rate under three repeated experimental trials, showing a strong positive correlation. At the lowest flow rate of 0.1 L/min, the output power begins at approximately 10 W (Trial 1), 3 W (Trial 2), and 1 W (Trial 3), indicating initial variability in system startup conditions. As the flow rate increases to 0.2 L/min, the power output rises significantly to around 25 W (Trial 1), 18 W (Trial 2), and 20 W (Trial 3), demonstrating the direct dependence of power generation on hydrogen supply.

In the intermediate range of 0.3–0.6 L/min, the power output continues to increase steadily across all trials. At 0.4 L/min, Trial 3 shows a slightly higher performance at approximately 52 W, compared to 48 W (Trial 1) and 35 W (Trial 2). By 0.5 L/min, all trials converge to similar values around 48–50 W, indicating improved system stability. At 0.6 L/min, the output reaches approximately 53 W (Trial 1), 62 W (Trial 2), and 60 W (Trial 3), highlighting some variation in system response but maintaining a consistent upward trend.

At higher flow rates between 0.7 and 1.0 L/min, the fuel cell delivers significantly higher power. At 0.7 L/min, the power increases to around 70 W (Trial 1), 80 W (Trial 2), and 70 W (Trial 3). By 0.8 L/min, all trials show values close to 75–80 W, and at 0.9 L/min, the output further rises to approximately 88 W (Trial 1), 90 W (Trial 2), and 96 W (Trial 3). At the maximum flow rate of 1.0 L/min, the system reaches peak performance with approximately 99 W (Trial 1), 100 W (Trial 2), and 104 W (Trial 3).

Overall, the results demonstrate a clear, consistent increase in fuel cell power output as the hydrogen flow rate increases, with values rising from below 10 W to over 100 W. The relatively small differences

between trials indicate good repeatability and system reliability, although minor fluctuations suggest sensitivity to operational parameters such as flow control, pressure stability, and fuel cell efficiency. These findings confirm that optimising the hydrogen flow rate is critical to maximising fuel cell performance in practical hydrogen energy systems.



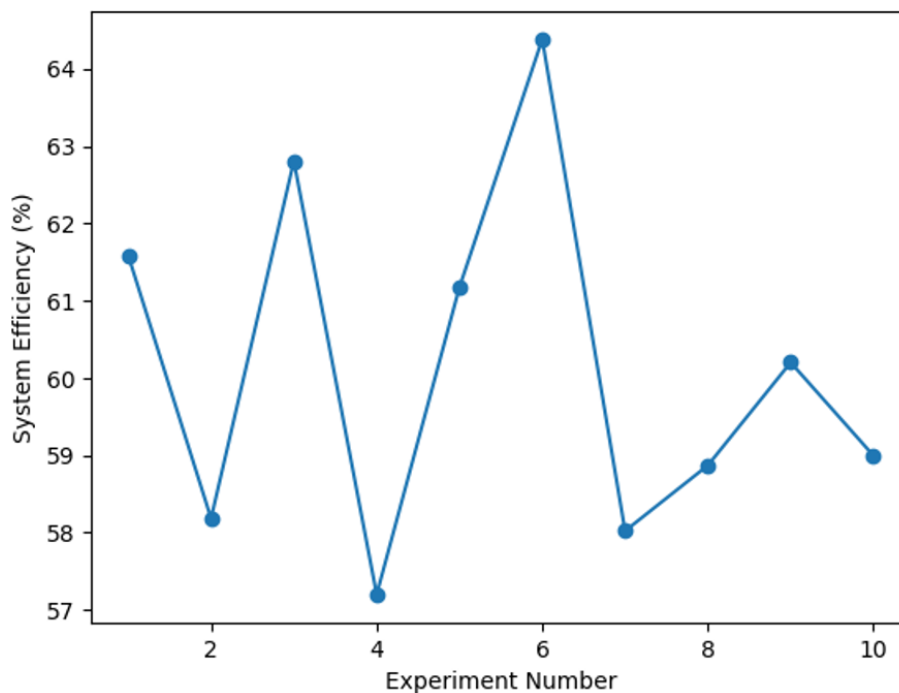
**Figure 5:** Fuel Cell Power Output as a Function of Hydrogen Flow Rate under Repeated Experimental Trials

**Figure 6** presents the system efficiency across ten repeated experimental runs, highlighting the consistency and variability of the hydrogen energy system. In the first experiment, the system efficiency is approximately 61.6%, followed by a decrease to 58.2% in the second run. The efficiency then increases significantly to about 62.8% in the third experiment, indicating improved system performance after initial stabilisation. However, a notable drop occurs in the fourth run, where efficiency reaches a low of approximately 57.2%, suggesting temporary fluctuations in operating conditions.

In the middle phase (experiments 5–7), the system efficiency shows both recovery and variation. In experiment 5, efficiency rises to around 61.2%, and then increases to a peak of approximately 64.4% in experiment 6, representing the highest performance observed in the dataset. This peak indicates optimal operating conditions during this run. However, in experiment 7, efficiency sharply declines again to about 58.0%, suggesting sensitivity to experimental or environmental factors such as temperature, pressure, or system stability.

In the later phase (experiments 8–10), the system efficiency stabilises within a narrower range. The efficiency gradually increases from 58.9% in experiment 8 to 60.2% in experiment 9, before slightly decreasing to 59.0% in experiment 10. This indicates that after initial fluctuations, the system tends to operate within a relatively stable efficiency band of approximately 58–60%. The reduced variability in this stage suggests improved control and repeatability of the experimental setup.

Overall, the results demonstrate that the hydrogen energy system achieves an average efficiency of 58–62%, with a maximum of 64.4% and a minimum of 57.2%. The fluctuations observed across repeated runs highlight the importance of maintaining stable operating conditions to ensure consistent performance. Despite these variations, the relatively narrow efficiency range confirms that the system exhibits good repeatability and reliability, making it suitable for further optimisation and scale-up in practical applications.



**Figure 6:** System Efficiency Across Repeated Experimental Runs

The novelty of this research lies in its integrated, systematic evaluation of hydrogen energy systems by combining production, storage, distribution, and utilisation processes within a single experimental framework, supported by repeated trials. Unlike many previous studies that focus on a single aspect, this work simultaneously analyses hydrogen production rate, electrolyser efficiency, storage capacity, and fuel cell performance under varying operational conditions. In addition, including multiple experimental runs provides a more robust assessment of system reliability and performance consistency. This comprehensive approach offers new insights into the interconnections among key parameters such as time, voltage, pressure, and flow rate, contributing to a deeper understanding of optimising hydrogen energy systems for sustainable, practical applications.

Despite its contributions, this study has several limitations that should be acknowledged. The experimental data are generated under controlled laboratory-scale conditions, which may not fully represent real-world or large-scale industrial applications. Variations in environmental factors such as temperature, pressure fluctuations, and long-term material degradation were not extensively examined. Furthermore, the study focuses primarily on technical performance parameters, with limited consideration of economic feasibility, lifecycle cost analysis, and large-scale infrastructure challenges. The number of experimental repetitions, although sufficient to demonstrate trends, may still be expanded to improve statistical accuracy. Future research should address these limitations by incorporating real-world conditions, larger datasets, and comprehensive techno-economic and environmental assessments.

#### 4. Conclusion

Based on the results and discussion, this study demonstrates that hydrogen energy systems have strong potential as a sustainable, efficient, and clean fuel solution. The hydrogen production process shows a consistent increase over time, with production rates rising from approximately 50 mL/min to over 90 mL/min, indicating stable and improving system performance during electrolysis. The electrolyser efficiency analysis reveals that optimal performance occurs at lower voltages (around 1.6–1.7 V), with efficiencies exceeding 70%, whereas higher voltages result in a gradual decline in efficiency due to

increased energy losses. These findings highlight the importance of optimising operating conditions to balance efficiency and production output. In terms of storage, hydrogen capacity increases significantly with pressure, reaching 14 kg or more at 700 bar, confirming the effectiveness of high-pressure storage systems. The fuel cell performance results further indicate that power output is directly proportional to hydrogen flow rate, increasing from below 10 W to over 100 W, demonstrating efficient energy conversion. Additionally, system efficiency across repeated experimental runs remains relatively stable at 58–64%, indicating good repeatability and reliability despite minor fluctuations.

Overall, integrating hydrogen production, storage, and utilisation processes into a single system shows promising performance across all evaluated parameters. The relatively small variations between repeated trials confirm the robustness of the experimental setup. These results suggest that hydrogen energy systems can be effectively optimised for higher efficiency and output, making them a viable pathway toward sustainable, low-carbon energy solutions in future energy systems.

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## References

- [1] F. Kourougianni *et al.*, “A comprehensive review of green hydrogen energy systems,” *Renew. Energy*, vol. 231, p. 120911, 2024, doi: <https://doi.org/10.1016/j.renene.2024.120911>.
- [2] Erdiwansyah, R. Mamat, M. F. Ghazali, F. Basrawi, and S. M. Rosdi, “Green hydrogen production and renewable energy storage integration: A review of technologies and system pathways,” *Energy Convers. Manag.* *X*, p. 101904, 2026, doi: <https://doi.org/10.1016/j.ecmx.2026.101904>.
- [3] A. Gani, M. Mahidin, E. Erdiwansyah, R. E. Sardjono, and D. Mokhtar, “Techno-Economic Assessment of Renewable Energy Integration in On-Grid Microgrids,” *Int. J. Energy Environ.*, vol. 1, no. 1, pp. 24–30, 2025.
- [4] B. C. Tashie-Lewis and S. G. Nnabuiife, “Hydrogen Production, Distribution, Storage and Power Conversion in a Hydrogen Economy - A Technology Review,” *Chem. Eng. J. Adv.*, vol. 8, p. 100172, 2021, doi: <https://doi.org/10.1016/j.ceja.2021.100172>.
- [5] Z. Bo, M. F. M. Said, E. Erdiwansyah, R. Mamat, and J. Xiaoxia, “A review of oxygen generation through renewable hydrogen production,” *Sustain. Chem. Clim. Action*, p. 100079, 2025, doi: <https://doi.org/10.1016/j.scca.2025.100079>.
- [6] S. M. Rosdi, R. E. Sardjono, and O. M. Ali, “Optimizing Biodiesel-Butanol Blends for Low CO<sub>2</sub> Emissions and Fuel Efficiency in Diesel Engines,” *Int. J. Energy Environ.*, vol. 1, no. 1, pp. 80–92, 2025, doi: <https://e-journal.scholar-publishing.org/index.php/ijee/article/view/124>.
- [7] P. K. Panda, B. Sahoo, and S. Ramakrishna, “Hydrogen production, purification, storage, transportation, and their applications: a review,” *Energy Technol.*, vol. 11, no. 7, p. 2201434, 2023.
- [8] M. A. Hamidi, “Carbon Footprint Reduction Potential of On-Grid Renewable Microgrids,” *Int. J. Energy Environ.*, vol. 1, no. 1, pp. 72–79, 2025, doi: <https://e-journal.scholar-publishing.org/index.php/ijee/article/view/119>.
- [9] Erdiwansyah, A. Gani, H. Desvita, R. Mamat, and M. F. Ghazali, “Analysis of the calorific value

- of biocoke from empty fruit bunches with temperature variations and FTIR characterization,” *Energy Storage Sav.*, vol. 4, no. 4, pp. 500–508, 2025, doi: <https://doi.org/10.1016/j.enss.2025.03.006>.
- [10] M. Ammar, B. O. Oyewale, A. Elseragy, I. M. Albayati, and A. M. Aliyu, “A Global Review of Blue and Green Hydrogen Fuel Production Technologies, Trends and Future Outlook to 2050,” *Fuels*, vol. 6, no. 4, p. 88, 2025. doi: 10.3390/fuels6040088.
- [11] A. Gani, “Heavy Metal Contamination in Biomass-Based Fuels: Risks and Mitigation Strategies,” *Int. J. Energy Environ.*, vol. 1, no. 1, pp. 56–63, 2025, doi: <https://e-journal.scholar-publishing.org/index.php/ijee/article/view/105>.
- [12] Muhibuddin, Erdiwansyah, A. Z. Syahir, R. Mamat, and R. E. Sardjono, “A review of optimization strategies for hybrid renewable energy systems toward sustainable clean energy,” *Results Eng.*, vol. 28, p. 108363, 2025, doi: <https://doi.org/10.1016/j.rineng.2025.108363>.
- [13] S. H. Osman, N. S. M. Yatim, O. S. J. Elham, N. Shaari, and Z. Zakaria, “Three decades of hydrogen energy research: a bibliometric analysis on the evolution of green hydrogen technologies,” *Sustain. Energy Fuels*, vol. 9, no. 12, pp. 3182–3202, 2025.
- [14] M. K. Akasyah and A. A. M. Redhwan, “Cylinder Pressure and Heat Release Analysis of Diesel-Butanol Blends at High Engine Load,” *Int. J. Energy Environ.*, vol. 2, no. 1, pp. 93–105, 2025, doi: <https://e-journal.scholar-publishing.org/index.php/ijee/article/view/113>.
- [15] N. Zubairu, L. Al Jabri, and A. Rejeb, “A review of hydrogen energy in renewable energy supply chain finance,” *Discov. Sustain.*, vol. 6, no. 1, p. 186, 2025, doi: 10.1007/s43621-025-01007-0.
- [16] A. Rezaee Jordehi, S. A. Mansouri, M. Tostado-Véliz, A. Iqbal, M. Marzband, and F. Jurado, “Industrial energy hubs with electric, thermal and hydrogen demands for resilience enhancement of mobile storage-integrated power systems,” *Int. J. Hydrogen Energy*, vol. 50, pp. 77–91, 2024, doi: <https://doi.org/10.1016/j.ijhydene.2023.07.205>.
- [17] H. Zhao *et al.*, “Resilience Assessment of Hydrogen-Integrated Energy System for Airport Electrification,” *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 2812–2824, 2022, doi: 10.1109/TIA.2021.3127481.
- [18] E. Bahagia, Juliansyah Harahap, Aida Sukma Yuri, “Evaluation of Domestic Wastewater Quality in Residential Areas and Treatment Alternatives with Constructed Wetland Technology,” *Int. J. Energy Environ.*, vol. 2, no. 1, pp. 118–126, 2025, doi: <https://e-journal.scholar-publishing.org/index.php/ijee/article/view/121>.
- [19] M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, and D. Hissel, “Hydrogen energy systems: A critical review of technologies, applications, trends and challenges,” *Renew. Sustain. Energy Rev.*, vol. 146, p. 111180, 2021, doi: <https://doi.org/10.1016/j.rser.2021.111180>.
- [20] R. Mamat, Erdiwansyah, M. F. Ghazali, S. M. Rosdi, Syafrizal, and Bahagia, “Strategic framework for overcoming barriers in renewable energy transition: A multi-dimensional review,” *Next Energy*, vol. 9, p. 100414, 2025, doi: <https://doi.org/10.1016/j.nxener.2025.100414>.
- [21] S. M. Erdiwansyah; Rosdi, “Performance and Emission Characteristics of Biodiesel-Butanol Blends in Variable Engine Speeds and Loads,” *Int. J. Energy Environ.*, vol. 2, no. 1, pp. 179–193, 2025, doi: <https://e-journal.scholar-publishing.org/index.php/ijee/article/view/132>.
- [22] I. Marouani *et al.*, “Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future,” *Processes*, vol. 11, no. 9, p. 2685, 2023. doi: 10.3390/pr11092685.
- [23] M. Laimon and T. Yusaf, “Towards energy freedom: Exploring sustainable solutions for energy independence and self-sufficiency using integrated renewable energy-driven hydrogen system,” *Renew. Energy*, vol. 222, p. 119948, 2024, doi: <https://doi.org/10.1016/j.renene.2024.119948>.
- [24] Erdiwansyah, R. Mamat, Syafrizal, M. F. Ghazali, F. Basrawi, and S. M. Rosdi, “Emerging Role of Generative AI in Renewable Energy Forecasting and System Optimization,” *Sustain. Chem. Clim. Action*, p. 100099, 2025, doi: <https://doi.org/10.1016/j.scca.2025.100099>.
- [25] A. Odenweller and F. Ueckerdt, “The green hydrogen ambition and implementation gap,” *Nat. Energy*, vol. 10, no. 1, pp. 110–123, 2025.
- [26] A. O. M. Maka and M. Mehmood, “Green hydrogen energy production: current status and potential,” *Clean Energy*, vol. 8, no. 2, pp. 1–7, 2024.

- [27] A. Tuluhong, Q. Chang, L. Xie, Z. Xu, and T. Song, “Current Status of Green Hydrogen Production Technology: A Review,” *Sustainability*, vol. 16, no. 20. p. 9070, 2024. doi: 10.3390/su16209070.
- [28] B. Amini Horri and H. Ozcan, “Green hydrogen production by water electrolysis: Current status and challenges,” *Curr. Opin. Green Sustain. Chem.*, vol. 47, p. 100932, 2024, doi: <https://doi.org/10.1016/j.cogsc.2024.100932>.