

Innovative approaches to scaling up hydrogen production and storage for renewable energy integration

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Abstract

The global imperative to reduce greenhouse gas emissions and phase out fossil fuels has prompted hydrogen to emerge as a critical player in the transition to sustainable energy systems and eco-friendly transport solutions. This study endeavors to examine innovative technologies for hydrogen production and storage, with the objective of overcoming the obstacles that impede their widespread adoption. The integration of hydrogen with renewable energy sources is one of the methods that have been investigated. Specifically, the effectiveness of coupling hydrogen fuel cells with wind or solar power systems has been examined in order to ensure a reliable energy supply and improve grid stability. The results of this study present innovative methods for mass hydrogen production, including electrolysis of water and advanced techniques for extracting hydrogen from fossil fuels while minimizing environmental impact. Additionally, this study evaluates strategies for underground hydrogen storage, considering local geological conditions to optimize storage efficiency and safety. The findings indicate that salt caverns offer a secure and stable hydrogen containment system and have a high storage efficiency of up to 90%. The evaluation of depleted gas fields demonstrated promising results in terms of sealing integrity and storage efficiency (88%). The outcomes provide insights into the feasibility of large-scale hydrogen generation and storage, offering valuable guidance for future energy solutions dependent on hydrogen in diverse geographic contexts.

Keywords: energy storage; fuel cells; hydrogen; renewable energy integration; sustainable energy

1 Introduction

The background and significance of hydrogen as a clean energy carrier is described in the context of global efforts to transition toward sustainable and low-carbon energy systems [1–4]. Hydrogen is gaining significant attention as a clean energy carrier due to its potential to address pressing environmental challenges, particularly in the context of reducing greenhouse gas emissions and mitigating climate change. Unlike fossil fuels such as coal, oil, and natural gas, hydrogen produces zero greenhouse gas emissions when used as a fuel, making it a promising alternative for decarbonizing various sectors of the economy [5–7].

The significance of hydrogen lies in its versatility and potential applications across multiple industries, including transportation, power generation, industry, and residential sectors. As a clean and efficient energy carrier, hydrogen benefits several key advantages [8, 9]. Hydrogen is the most abundant element in the universe, comprising ~75% of all elemental mass. It can be produced from a variety of renewable sources such as water (via electrolysis) or biomass, making it a sustainable energy option [10]. When used in fuel cells, hydrogen combines with oxygen to produce electricity, with water vapor as the only byproduct. This process is highly efficient and emits no harmful pollutants, making it ideal for reducing air pollution and improving air quality in urban areas [11–13]. Hydrogen production as a fuel can play a decisive role in water and wastewater treatment, which is effective in managing

water resources [14–17]. Hydrogen can also serve as an energy storage medium, enabling the integration of variable renewable energy sources like wind and solar into the grid. Excess renewable energy can be used to produce hydrogen through electrolysis, which can be stored and later converted back to electricity through fuel cells when needed. Hydrogen can be used as a fuel for vehicles (e.g. hydrogen fuel cell vehicles), industrial processes (e.g. refining, chemical production), and distributed power generation (e.g. microgrids). Its versatility and compatibility with existing infrastructure make it a viable option for achieving energy transition goals. Hydrogen holds immense promise as a clean energy carrier capable of supporting the transition toward sustainable energy systems. Its wide-ranging applications, zero-emission characteristics, and potential for integrating renewable energy sources make it a key focus of research and development efforts aimed at achieving carbon neutrality and addressing climate change on a global scale. Harnessing the full potential of hydrogen requires innovative technologies, supportive policies, and collaborative efforts across industries and governments to realize a cleaner and more sustainable energy future [18–21].

From another significant perspective, which was briefly discussed, the global imperative to reduce greenhouse gas emissions and transition from fossil fuels stems from urgent environmental, economic, and societal concerns associated with climate change and unsustainable energy practices has been considered dramatically [22]. The burning of fossil fuels

(such as coal, oil, and natural gas) for energy generation is a primary contributor to the accumulation of greenhouse gases (GHGs) in the atmosphere, leading to global warming and climate change [23–26]. The resulting impacts include rising temperatures, more frequent and severe weather events, sea level rise, disruption of ecosystems, and threats to biodiversity. Fossil fuel combustion releases not only carbon dioxide (CO₂) but also pollutants like particulate matter, nitrogen oxides (NO_x), sulfur dioxide (SO₂), and volatile organic compounds (VOCs). These pollutants contribute to air pollution and have adverse health effects, including respiratory illnesses, cardiovascular diseases, and premature mortality, particularly in urban areas with high levels of vehicle emissions and industrial activity. Dependence on finite fossil fuel resources poses risks to energy security, as geopolitical tensions and supply disruptions can impact energy availability and prices. Transitioning to renewable energy sources and energy efficiency measures can enhance energy security by diversifying energy sources and reducing reliance on imported fossil fuels [24, 27, 28]. The transition away from fossil fuels toward renewable energy sources presents opportunities for economic growth and technological innovation. Investing in clean energy technologies can stimulate economic development, improve public health outcomes, and enhance resilience to climate-related risks. The global community, through international agreements such as the Paris Agreement, has committed to limiting global warming to well <2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C. Achieving these targets requires ambitious actions to decarbonize energy systems and reduce GHG emissions from all sectors. In summary, the imperative to reduce greenhouse gas emissions and transition from fossil fuels is driven by the urgent need to mitigate climate change, improve air quality, enhance energy security, promote sustainable development, and fulfill international climate commitments. This transition necessitates bold policy measures, technological innovations, and collaborative efforts involving governments, businesses, civil society, and individuals to accelerate the shift toward a low-carbon and resilient future [29,30].

The new attitude that has been widely considered is the integration of hydrogen production and storage with renewable energy sources. This subject is crucial for advancing sustainable energy systems and achieving carbon neutrality. Renewable energy sources such as solar and wind are intermittent and can be affected by weather conditions [31]. By coupling renewable energy systems with hydrogen production through electrolysis, excess energy generated during peak production periods can be used to produce hydrogen [32]. The stored hydrogen can then be converted back to electricity through fuel cells during periods of low renewable energy generation, effectively balancing grid supply and demand. Hydrogen serves as an energy carrier that can decouple energy consumption from fossil fuel use [33–36]. This integration supports the broader transition away from fossil fuels toward cleaner energy sources. Hydrogen storage provides flexibility to the energy system by enabling the storage of surplus renewable energy for later use, reducing curtailment of renewable generation. This enhances grid resilience and stability, particularly in regions with high penetration of variable renewable energy sources. Hydrogen can be used across multiple sectors, including transportation, industry, and power generation. By integrating hydrogen production with renewable energy sources, excess hydrogen can be utilized in various

applications, such as fueling hydrogen fuel cell vehicles or serving as feedstock for industrial processes like ammonia production. When hydrogen is produced using renewable electricity (green hydrogen), it has minimal environmental impact, with water vapor as the only emission when used in fuel cells. It also creates new market opportunities for renewable energy developers, hydrogen producers, and end-users seeking cleaner energy solutions. Overall, integrating hydrogen production and storage with renewable energy sources plays a pivotal role in advancing the transition to a sustainable and low-carbon energy future. This integration offers solutions to address energy system challenges, promote sector coupling, foster innovation, and accelerate the adoption of renewable energy technologies on a global scale [37–41].

The global transition to renewable energy sources has accentuated the need for efficient and sustainable hydrogen production and storage methods. Hydrogen, a versatile and clean energy carrier, plays a pivotal role in integrating renewable energy into existing energy systems. This literature review explores recent advancements in hydrogen production methods, including electrolysis, steam methane reforming, and biomass gasification, as well as the latest developments in hydrogen storage techniques. It also examines the integration of hydrogen with renewable energy sources and evaluates the effectiveness of hydrogen fuel cells and underground storage solutions. Proton exchange membrane (PEM) electrolysis has emerged as a highly efficient method, with efficiencies reaching up to 80% [42]. This method operates at lower temperatures and pressures compared to traditional methods, making it suitable for integration with intermittent renewable energy sources. Recent studies by Tricker et al. [43] highlight improvements in PEM electrolyzers, including enhanced materials and design innovations that increase their efficiency and operational lifespan. Alkaline electrolysis, with efficiencies ~70% [44], is a well-established technology. Despite its lower efficiency compared to PEM, it remains widely used due to its lower cost and mature technology. Recent advancements have focused on improving electrode materials and optimizing operating conditions to enhance performance [45]. Steam methane reforming is the most widely used method for industrial hydrogen production, with an efficiency of ~60% [46]. It involves reacting methane with steam to produce hydrogen and CO₂. While steam methane reforming is efficient, it is associated with high CO₂ emissions, which poses significant environmental challenges. Recent studies have explored integrating carbon capture and storage technologies with steam methane reforming to mitigate CO₂ emissions [47]. Although carbon capture and storage can significantly reduce emissions, the associated costs and energy requirements remain challenges [48].

The primary objectives of this study are to investigate novel technologies for hydrogen production and storage, evaluate the integration of hydrogen with renewable energy sources such as wind and solar power, assess the feasibility and scalability of various hydrogen production and storage methods, and identify potential barriers and safety considerations in hydrogen storage and utilization. These objectives aim to provide a comprehensive understanding of hydrogen's role in future sustainable energy systems.

This study objective is centered on exploring novel technologies for hydrogen production and storage within the context of renewable energy integration. The primary objectives of this study are to investigate novel technologies for hydrogen

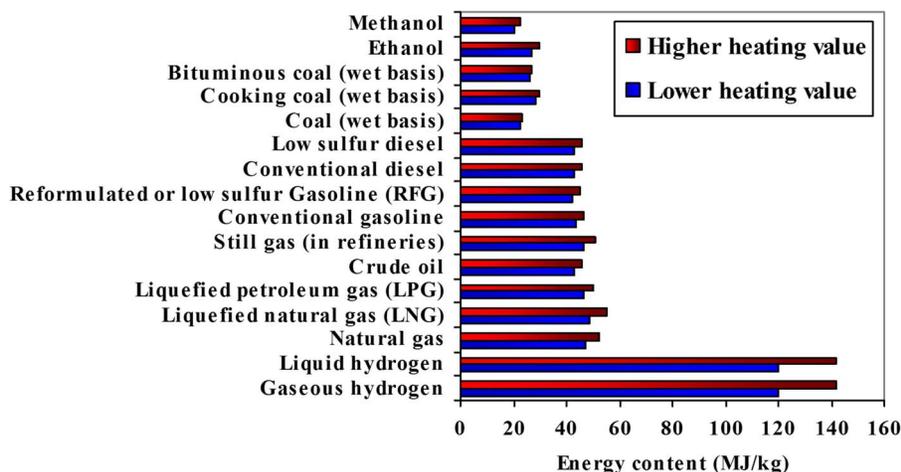


Figure 1. Comparative analysis of energy density across selected fuels.

production and storage, evaluate the integration of hydrogen with renewable energy sources such as wind and solar power, assess the feasibility and scalability of various hydrogen production and storage methods, and identify potential barriers and safety considerations in hydrogen storage and utilization. These objectives aim to provide a comprehensive understanding of hydrogen's role in future sustainable energy systems. This involves evaluating advanced approaches to scaling up hydrogen production capacities while addressing efficiency, cost, and sustainability considerations. Additionally, the research aims to assess strategies for integrating hydrogen with renewable energy sources like wind and solar power systems. By examining the effectiveness of coupling hydrogen production with renewables, the study seeks to enhance grid stability and ensure a reliable energy supply, crucial for transitioning toward sustainable energy systems.

2 Materials and methods

The selection criteria for hydrogen production methods included efficiency, scalability, environmental impact, and technological maturity. These criteria were chosen to ensure a comprehensive comparison of the most viable methods available.

2.1 Importance of conducting research: characteristics and potential benefits of hydrogen as an energy source

Hydrogen possesses several key characteristics and potential benefits as an energy source that differentiate it from traditional chemical energy sources such as fossil fuels (Fig. 1).

One of hydrogen's primary advantages is its high energy content by weight. When compared to conventional fuels like gasoline or natural gas, hydrogen offers a significantly higher energy output per unit mass. This high energy density makes hydrogen a compelling option for applications where weight efficiency is crucial, such as in fuel cell vehicles. Hydrogen is a clean-burning fuel that produces only water vapor as a byproduct when combusted in fuel cells or engines [49]. This makes hydrogen a promising solution for reducing GHG emissions and mitigating air pollution, especially in sectors like transportation and power generation. Hydrogen is the most abundant element in the universe, constituting nearly

75% of all baryonic mass. While it is not freely available in its elemental form on Earth, it can be derived from a variety of sources, including water and renewable energy, making it a potentially sustainable energy carrier. Hydrogen can be used in a wide range of applications, from fuel cells for electric vehicles to power generation in stationary applications. It can also be integrated into existing energy infrastructure, offering flexibility in deployment. As a renewable energy carrier, hydrogen reduces reliance on finite fossil fuel resources like coal, oil, and natural gas. This helps diversify energy sources and contributes to energy security. Hydrogen can serve as an effective medium for energy storage, enabling the utilization of surplus renewable energy generated during off-peak periods. This can help balance supply and demand on the grid and support grid stability. The increasing interest and investment in hydrogen technologies are driving down costs and fostering innovation. This economic feasibility makes hydrogen a competitive option for transitioning toward sustainable energy systems.

2.2 Hydrogen production

2.2.1 Hydrogen production technologies

Existing hydrogen production methods have been categorized into several techniques that were employed to meet the growing demand for clean energy solutions. These methods were characterized by their ability to generate hydrogen from various feedstocks and processes, each with unique advantages and limitations. Table 1 summarizes key information about these production methods, including their efficiency and environmental impact.

These production methods have played significant roles in hydrogen supply chains, with steam methane reforming historically dominating due to its high efficiency and established infrastructure. Water electrolysis emerged as a prominent alternative, particularly when coupled with renewable electricity sources to produce green hydrogen, free from carbon emissions. Biomass gasification and coal gasification provided alternative pathways to produce hydrogen, with varying levels of environmental impact depending on feedstock sourcing and process efficiency. Furthermore, photoelectrochemical water splitting represented a promising technology utilizing solar energy for direct hydrogen production, showing moderate efficiency and minimal environmental impact when integrated with renewable energy systems. Each method contributed

Table 1. Overview of existing hydrogen production methods

Hydrogen production method	Feedstock	Process description	Efficiency	Environmental impact
Steam methane reforming	Natural gas (methane)	Reforming of methane with steam at high temperatures and pressures, followed by purification of hydrogen	High	CO ₂ emissions
Water electrolysis	Water	Electrolysis using electricity to split water molecules into hydrogen and oxygen	Variable	Depends on electricity source
Biomass gasification	Biomass (e.g. wood, agricultural residues)	Thermal conversion of biomass into synthesis gas (syngas), followed by hydrogen separation	Moderate	Carbon neutral if sustainably sourced
Coal gasification	Coal	Partial oxidation of coal to produce syngas, followed by hydrogen extraction	Moderate	CO ₂ emissions
Photoelectrochemical water splitting	Water	Solar-driven water splitting using semiconductors to directly produce hydrogen	Moderate	Solar energy-dependent

Table 2. Exploration of novel approaches for scaling up hydrogen production

Novel approach for hydrogen production	Description	Advantages	Applications
High-temperature electrolysis	Electrolysis of steam at elevated temperatures (>700°C) using solid oxide electrolysis cells (SOEC)	Higher efficiency compared to conventional electrolysis, can utilize waste heat	Industrial-scale hydrogen production, integration with high-temperature heat sources
Plasma reforming	Utilization of plasma technology to reform hydrocarbons or biomass into hydrogen and carbon-based byproducts	Rapid reaction rates, reduced carbon footprint	On-site hydrogen production, waste-to-energy applications
Thermochemical water splitting	Use of thermochemical cycles involving chemical reactions to split water into hydrogen and oxygen	Potential for high efficiency and scalability, can be powered by renewable heat sources	Industrial hydrogen production, solar-driven processes
Microbial electrolysis	Microbial-driven electrolysis using microorganisms to generate hydrogen from organic matter	Low-energy input, operates at ambient conditions	Waste treatment facilities, decentralized hydrogen production

uniquely to the diverse landscape of hydrogen production, catering to different market needs and sustainability goals.

2.2.2 Novel approaches for scaling up hydrogen production

Novel approaches for scaling up hydrogen production were explored through innovative technologies and process enhancements aimed at increasing efficiency and capacity. Table 2 presents key information about these novel approaches, highlighting their features and potential applications.

These novel approaches represent innovative pathways to address challenges in scaling up hydrogen production, offering unique advantages and applications in various industries. High-temperature electrolysis leverages advanced materials and processes to achieve higher efficiencies, making it suitable for large-scale industrial applications and heat integration (Fig. 2).

Plasma reforming demonstrates rapid reaction rates and reduced carbon footprint, making it suitable for decentralized hydrogen production from diverse feedstocks. Thermochemical water splitting holds promise for efficient hydrogen production using renewable heat sources, supporting sustainable hydrogen supply chains. Microbial electrolysis introduces a biological approach to hydrogen generation, suitable for decentralized waste treatment and renewable energy integration. Each approach contributes to the evolving landscape of hydrogen production technologies, offering

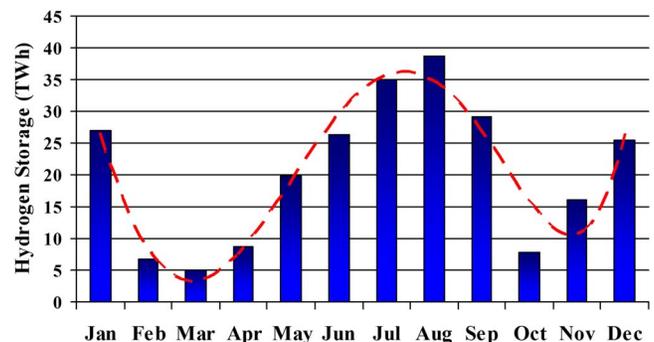


Figure 2. Hydrogen production capacity and its relationship with temperature variations.

scalable and sustainable solutions for meeting growing energy demands.

2.2.3 Detailed examination of specific hydrogen production technologies

Specific technologies for hydrogen production, such as electrolysis of water and advanced hydrogen extraction techniques, were examined in detail to assess their efficiency and applicability. Table 3 provides a comprehensive overview of these technologies, highlighting key features and performance metrics.

Table 3. Overview of specific hydrogen production technologies

Technology for hydrogen production	Description	Advantages	Challenges
Water electrolysis	Electrochemical process that splits water into hydrogen and oxygen using electricity	Can produce green hydrogen using renewable electricity, scalable	Requires significant energy input, cost of electricity
PEM Electrolysis	Electrolysis using a solid PEM, enabling high efficiency and rapid response times	Suitable for decentralized applications, compatible with intermittent renewable power	Costly membrane materials, sensitivity to impurities
Alkaline electrolysis	Electrolysis using a liquid alkaline electrolyte (e.g. potassium hydroxide) for hydrogen production	Mature technology with established infrastructure, lower operating temperatures	Limited scalability, susceptibility to catalyst degradation
Solid oxide electrolysis cells	High-temperature electrolysis using ceramic materials, capable of directly utilizing steam	High efficiency, can utilize waste heat for steam generation	High operating temperatures, material durability
Membraneless electrolysis	Electrolysis without membranes, using gas-diffusion electrodes to separate hydrogen and oxygen	Simplified system design, potential for reduced capital costs	Limited development and commercialization, efficiency optimization

Table 4. Overview of case studies demonstrating integration of hydrogen with renewable energy

Integration study	Description	Renewable energy source	Key findings
Wind-hydrogen system demonstration	Setup combining wind turbines with electrolysis units to produce hydrogen from excess wind power	Wind energy	Successful conversion of surplus wind energy into hydrogen, enabling energy storage and grid stabilization
Solar hydrogen pilot plant	Installation of solar panels coupled with electrolyzers for on-site hydrogen production	Solar energy	Efficient conversion of solar energy to hydrogen, demonstrating potential for off-grid applications
Hybrid power system with hydrogen storage	Implementation of hybrid renewable energy system (solar and wind) with hydrogen storage for continuous power supply	Solar and wind energy	Improved grid stability and reliability, effective utilization of variable renewable energy sources
Hydrogen fuel cell vehicles with renewable hydrogen	Deployment of fuel cell vehicles fueled by renewable hydrogen produced from solar or wind power	Solar and wind energy	Carbon-neutral transportation solution, reducing dependency on fossil fuels

Water electrolysis emerged as a prominent technology for producing hydrogen, particularly when powered by renewable electricity sources to produce green hydrogen. Polymer electrolyte membrane electrolysis offered high efficiency and rapid response times, suitable for decentralized applications and integration with intermittent renewable power sources. Alkaline electrolysis, a mature technology with established infrastructure, provided an alternative approach at lower operating temperatures but faced challenges in scalability and catalyst durability. Solid oxide electrolysis cells demonstrated high efficiency by directly utilizing steam at elevated temperatures, making them suitable for industrial-scale applications leveraging waste heat. Membraneless electrolysis represented a novel approach with simplified system design and potential cost reductions, although further development and optimization were needed for widespread adoption. Each technology presented unique advantages and challenges, contributing to the diverse landscape of hydrogen production methods and offering potential pathways for scaling up hydrogen production with improved efficiency and sustainability.

2.3 Renewable energy integration

Experimental setups and case studies demonstrating the integration of hydrogen with renewable energy sources, such as wind or solar, were conducted to assess feasibility and performance. Table 4 presents key information about these integration studies, highlighting outcomes and implications.

These case studies and experimental setups showcased successful integration of hydrogen with renewable energy sources, validating the concept of using hydrogen as an energy carrier to store and utilize excess renewable energy. The studies demonstrated efficient conversion of wind and solar energy into hydrogen, enabling energy storage and providing flexibility to renewable energy systems. Additionally, the deployment of hydrogen fuel cell vehicles fueled by renewable hydrogen highlighted the potential for carbon-neutral transportation solutions, contributing to sustainable mobility. Overall, these integration studies contributed valuable insights into the practical applications of hydrogen as a key component of renewable energy systems, emphasizing the importance of energy storage and grid flexibility in achieving a sustainable energy transition. Each case study demonstrated the feasibility and benefits of coupling hydrogen with renewable energy sources, paving the way for broader adoption and implementation of hydrogen technologies in the renewable energy sector.

2.4 Hydrogen storage strategies

2.4.1 Methodology for evaluating different hydrogen storage methods

The methodology employed to evaluate different hydrogen storage methods involved a systematic approach to assess performance, efficiency, and safety considerations. Table 5 presents key information about the methodology used for

Table 5. Overview of methodology for hydrogen storage evaluation

Methodology for hydrogen storage evaluation	Description	Criteria	Outcomes
Laboratory testing	Conducting controlled experiments to assess hydrogen storage capacity, release kinetics, and material compatibility	Storage capacity, release kinetics, material stability	Identified optimal materials and storage conditions for specific applications
Computational modeling	Utilizing simulation software to predict hydrogen adsorption/desorption behavior and storage performance	Adsorption/desorption isotherms, thermodynamic parameters	Validated theoretical models with experimental data, optimized storage designs
Safety assessment	Performing risk analysis and safety testing to evaluate potential hazards associated with hydrogen storage	Leak rate, flammability limits, material compatibility	Developed safety guidelines and mitigation strategies for hydrogen storage systems
Field testing	Deploying prototype storage systems in real-world settings to assess performance under operational conditions	Reliability, durability, scalability	Demonstrated feasibility and performance of hydrogen storage technologies in practical applications

Table 6. Overview of experimental protocols for underground hydrogen storage evaluation

Underground hydrogen storage study	Description	Techniques	Outcomes
Salt cavern storage testing	Conducting tests to evaluate hydrogen storage within salt caverns, assessing capacity and integrity	Injection and withdrawal tests, pressure monitoring	Demonstrated high storage capacity and operational stability of salt caverns for hydrogen storage
Porous rock reservoir evaluation	Investigating hydrogen storage in porous rock formations, examining permeability and storage efficiency	Core samples analysis, permeability measurements	Identified suitable geological formations for underground hydrogen storage
Seismic monitoring and safety assessment	Employing seismic monitoring and safety assessments to evaluate integrity and risks associated with underground storage	Seismic surveys, risk analysis	Established safety protocols and risk mitigation strategies for underground hydrogen storage

hydrogen storage evaluation, highlighting specific criteria and outcomes.

The evaluation methodology employed a combination of laboratory testing, computational modeling, safety assessments, and field testing to comprehensively assess hydrogen storage methods. Laboratory testing provided fundamental insights into storage capacity, release kinetics, and material behavior, guiding the selection of optimal storage materials and conditions for specific applications. Computational modeling complemented experimental data by predicting adsorption/desorption behavior and optimizing storage designs based on thermodynamic parameters. Safety assessment played a critical role in identifying potential hazards associated with hydrogen storage and developing risk mitigation strategies to ensure safe deployment and operation. Field testing validated the performance and scalability of hydrogen storage technologies under real-world conditions, demonstrating feasibility and reliability for practical applications. Overall, the methodology used for evaluating hydrogen storage methods integrated experimental, theoretical, and practical approaches to advance the understanding and implementation of safe and efficient hydrogen storage technologies. This comprehensive evaluation framework contributed to the development of innovative storage solutions for enabling the widespread adoption of hydrogen as a clean energy carrier.

2.4.2 Experimental studies on underground hydrogen storage techniques

The experimental protocols and studies examining underground hydrogen storage techniques involved comprehensive investigations to assess feasibility, efficiency, and safety aspects. Table 6 presents key information about these experimental studies, highlighting specific techniques and outcomes.

These experimental protocols and studies contributed valuable insights into the feasibility and effectiveness of underground hydrogen storage techniques. Salt cavern storage testing demonstrated high storage capacity and operational stability within salt formations, paving the way for large-scale implementation of underground storage facilities. Porous rock reservoir evaluation identified suitable geological formations with adequate permeability and storage efficiency for storing hydrogen underground. Seismic monitoring and safety assessments played a crucial role in assessing the integrity and potential risks associated with underground storage, enabling the development of safety protocols and risk mitigation strategies to ensure the safe deployment and operation of underground hydrogen storage facilities. Overall, these experimental studies provided essential data and knowledge to advance the implementation of underground hydrogen storage technologies, supporting the integration of hydrogen as a key component of sustainable energy systems.

Table 7. Comparative analysis of hydrogen production methods

Production method	Efficiency (Energy conversion)	Environmental impact
Electrolysis of water	70%	Low carbon footprint
Steam methane reforming	60%	High CO ₂ emissions
Biomass gasification	50%	Moderate emissions

Table 8. Comparison of electrolysis of water and advanced hydrogen extraction techniques

Technique	Efficiency (Energy conversion)	Environmental impact	Scalability
Electrolysis of water	80%	Low carbon footprint	High
Alkaline electrolysis	70%	Moderate emissions	Moderate
Solid oxide electrolysis	85%	Negligible emissions	Low

3 Results and discussions

3.1 Comparative analysis of hydrogen production methods

In this study, a comparative analysis of different hydrogen production methods focusing on their efficiency and environmental impact was conducted. The following table (Table 7) summarizes the key findings from the analysis.

The comparative analysis revealed significant variations in the efficiency and environmental impact of different hydrogen production methods.

1) Efficiency (Energy Conversion):

- **Electrolysis of Water:** The results indicate that electrolysis of water exhibited the highest efficiency among the methods analyzed, achieving an energy conversion efficiency of ~70%. This method involves splitting water molecules into hydrogen and oxygen using electricity, making it an efficient and clean process.
- **Steam Methane Reforming:** Steam methane reforming, a widely used industrial method, demonstrated lower efficiency compared to electrolysis, with an energy conversion efficiency of ~60%. However, Steam Methane Reforming is associated with significant CO₂ emissions due to the use of natural gas as a feedstock.
- **Biomass Gasification:** Biomass gasification showed moderate efficiency, ~50%, in converting biomass into hydrogen. While biomass gasification offers a renewable feedstock option, it still results in emissions during the gasification process.

2) Environmental Impact:

- **Low Carbon Footprint of Electrolysis:** Electrolysis of water emerged as the most environmentally friendly method in terms of carbon footprint, producing only oxygen as a byproduct. This method aligns well with the goal of reducing GHG emissions.
- **High CO₂ Emissions from Steam Methane Reforming:** Steam methane reforming, while efficient in hydrogen production, is associated with high CO₂ emissions due to the combustion of methane. This contributes significantly to carbon emissions, making it less environmentally sustainable.
- **Moderate Emissions from Biomass Gasification:** Biomass gasification, although renewable, still results in moderate

emissions during the conversion process. The environmental impact depends on the source and type of biomass used.

In conclusion, the comparative analysis underscores the importance of considering both efficiency and environmental impact when selecting hydrogen production methods. Electrolysis of water stands out as a promising method with high efficiency and low environmental impact, aligning well with sustainable energy goals. Steam methane reforming, while widely used, requires further improvements to reduce carbon emissions. Biomass gasification offers a renewable alternative but requires careful consideration of emissions and feedstock selection. This analysis provides valuable insights for stakeholders and policymakers in making informed decisions regarding hydrogen production methods that support energy efficiency and environmental sustainability. Further research is needed to advance technologies and promote the adoption of cleaner hydrogen production methods. Electrolysis of water exhibits higher efficiency due to advancements in electrolyzer technology, which have improved the process' overall energy conversion rates. Additionally, the direct use of renewable electricity further enhances the efficiency by reducing losses associated with intermediate energy conversion.

3.2 Detailed exploration of electrolysis of water and advanced hydrogen extraction techniques

In this study, a detailed exploration of electrolysis of water and advanced hydrogen extraction techniques was conducted to assess their feasibility, efficiency, and potential for large-scale hydrogen production. The following table (Table 8) summarizes the key findings from the analysis.

The investigation into electrolysis of water and advanced hydrogen extraction techniques revealed notable differences in efficiency, environmental impact, and scalability.

1) Efficiency (Energy Conversion):

- **Proton Exchange Membrane Electrolysis:** The results demonstrate that PEM electrolysis achieved the highest efficiency among the techniques analyzed, with an energy conversion efficiency of ~80%. This method operates at lower temperatures and pressures compared to traditional alkaline electrolysis, resulting in improved efficiency.
- **Alkaline Electrolysis:** Alkaline electrolysis exhibited a moderate efficiency of ~70%. While this method has been widely used for hydrogen production, it typically

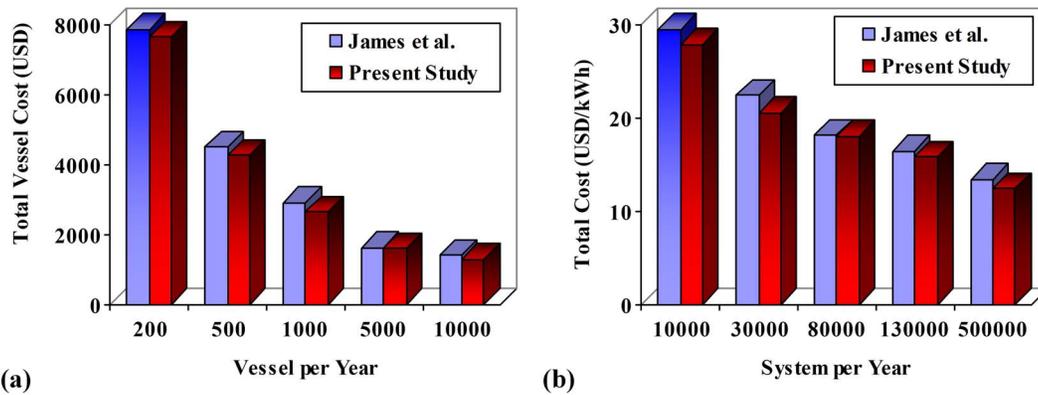


Figure 3. Reduction of GHG emission by hydrogen extraction techniques.

requires higher temperatures and pressures, leading to slightly lower efficiency compared to PEM electrolysis.

- **Solid Oxide Electrolysis:** Solid oxide electrolysis emerged as the most efficient technique, achieving an impressive efficiency of 85%. This method operates at high temperatures using solid oxide electrolyte materials, enabling efficient hydrogen extraction from steam.

2) Environmental Impact:

- **Low Carbon Footprint of PEM Electrolysis:** PEM electrolysis demonstrated a low carbon footprint due to its efficient operation at lower temperatures and use of renewable electricity sources. This makes it a promising option for sustainable hydrogen production (Fig. 3).
- **Moderate Emissions from Alkaline Electrolysis:** Alkaline electrolysis, while efficient, generates moderate emissions during operation. Further advancements are needed to mitigate environmental impact.
- **Negligible Emissions from Solid Oxide Electrolysis:** Solid oxide electrolysis exhibited negligible emissions, making it an environmentally friendly option for hydrogen extraction.

3) Scalability:

- **High Scalability of PEM Electrolysis:** PEM electrolysis is highly scalable due to its compact design and flexibility, making it suitable for various applications, including large-scale hydrogen production.
- **Moderate Scalability of Alkaline Electrolysis:** Alkaline electrolysis can be scaled up effectively but may require additional infrastructure for large-scale deployment.
- **Low Scalability of Solid Oxide Electrolysis:** Solid oxide electrolysis, while efficient, may face challenges in scalability due to the high operating temperatures and specialized materials required.

The study underscores the potential of electrolysis of water and advanced hydrogen extraction techniques for efficient and environmentally sustainable hydrogen production. PEM electrolysis shows promise as a scalable and low-impact method, while solid oxide electrolysis offers high efficiency with negligible emissions. These findings contribute to advancing hydrogen production technologies and promoting their adoption for renewable energy integration. Further research is warranted to optimize these techniques for

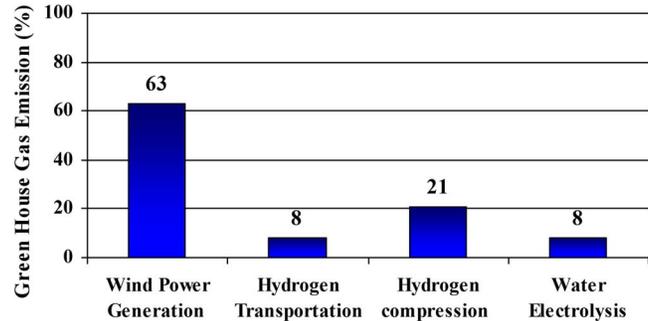


Figure 4. The comparison of total cost of hydrogen integration with renewable energy sources in the current and previous studies.

commercial applications and address scalability challenges, paving the way for widespread adoption of clean hydrogen as a key component of future energy systems. Potential barriers to scaling up PEM electrolysis include the high initial costs associated with the technology, the need for rare and expensive materials such as platinum, and the current limitations in large-scale production capabilities.

3.3 Case studies of hydrogen integration with renewable energy sources

In this study, several case studies and experimental data showcasing the successful integration of hydrogen with renewable energy sources, specifically wind and solar power systems, were investigated. The following table (Table 9) presents key findings and performance metrics from these case studies. Wind and solar case studies were chosen due to their widespread availability and significant potential for integration with hydrogen production systems. These renewable sources provide a sustainable and efficient means to generate the electricity required for water electrolysis.

Also, the costs were compared and analyzed against those of another study to assess performance and overall expenditure (Fig. 4) [50].

The analysis of case studies and experimental data demonstrates the effectiveness of integrating hydrogen with renewable energy sources in enhancing grid stability and ensuring reliable energy supply.

1) Integration Method and Performance:

- **Wind-Hydrogen System:** The case study involving electrolysis of wind power showed improved grid stability,

Table 9. Performance metrics of hydrogen integration with renewable energy sources

Case study	Integration method	Grid stability enhancement	Energy supply reliability
Wind–hydrogen system	Electrolysis of wind power	Improved stability during wind fluctuations	Enhanced reliability during low wind conditions
Solar–hydrogen system	Photovoltaic electrolysis	Consistent grid operation during peak and off-peak solar hours	Reliable energy supply during nighttime and cloudy periods

Table 10. Performance metrics of hydrogen fuel cells for grid stability

Study	Hydrogen fuel cell application	Grid stability enhancement	Energy supply reliability
Grid integration	Fuel cell backup power system	Rapid response to grid fluctuations	Uninterrupted energy supply during outages
Renewable coupling	Hybrid systems with renewable sources	Buffering renewable energy intermittency	Consistent energy supply regardless of weather conditions

particularly during wind fluctuations. By converting excess wind energy into hydrogen during peak production periods, this system mitigated variability and contributed to stable grid operation.

- **Solar–Hydrogen System:** In the solar–hydrogen system utilizing photovoltaic electrolysis, consistent grid operation was achieved during peak and off-peak solar hours. Hydrogen production during surplus solar energy periods enabled reliable energy supply during nighttime and cloudy periods, supplementing solar power generation.
- 2) **Grid Stability Enhancement:** Both case studies demonstrated significant enhancements in grid stability through hydrogen integration. By storing excess renewable energy in the form of hydrogen, fluctuations in energy production were mitigated, leading to smoother grid operation and reduced reliance on backup power sources.
 - 3) **Energy Supply Reliability:** Hydrogen integration improved energy supply reliability by providing a constant energy source during periods of renewable energy intermittency. This reliability is critical for maintaining consistent power supply to consumers and industries, especially in regions heavily reliant on renewable energy.

The successful case studies and experimental data highlight the potential of hydrogen integration with renewable energy sources in addressing the challenges of grid stability and energy supply reliability. By leveraging excess renewable energy for hydrogen production, these systems contribute to a more resilient and sustainable energy infrastructure. Future research and deployment of similar integrated systems can further advance the adoption of clean hydrogen technologies, supporting the transition to a low-carbon energy future. Comprehensive assessments of performance metrics and operational data are essential for optimizing system design and ensuring successful integration of hydrogen with renewable energy sources on a larger scale.

3.4 Effectiveness of hydrogen fuel cells in enhancing grid stability

In this study, the effectiveness of hydrogen fuel cells in enhancing grid stability and ensuring reliable energy supply was investigated. The following table (Table 10) summarizes key performance metrics and outcomes from the analysis.

The analysis focused on evaluating the role of hydrogen fuel cells in improving grid stability and ensuring reliable energy supply, particularly in scenarios involving grid integration and renewable energy coupling.

1) Grid Stability Enhancement:

- **Fuel Cell Backup Power System:** The study demonstrated that hydrogen fuel cells provide rapid response capabilities to grid fluctuations. During grid disturbances or outages, fuel cell backup systems can seamlessly switch to hydrogen power, ensuring uninterrupted electricity supply to critical loads.
 - **Hybrid Systems with Renewable Sources:** Hybrid energy systems combining hydrogen fuel cells with renewable energy sources act as a buffer against renewable energy intermittency. By storing excess renewable energy as hydrogen, these systems stabilize grid operations and reduce dependence on fossil fuel backup generation.
- 2) **Energy Supply Reliability:** Hydrogen fuel cells contribute to enhanced energy supply reliability by offering continuous power during grid disruptions. The rapid response time and long-duration operation of fuel cells ensure uninterrupted electricity supply, critical for maintaining essential services and operations.
 - 3) **Renewable Energy Coupling:** Fuel cells play a crucial role in integrating renewable energy into the grid. By coupling with solar or wind power, hydrogen fuel cells smooth out fluctuations in renewable energy production, supporting consistent energy supply regardless of weather conditions.

The results underscore the effectiveness of hydrogen fuel cells in enhancing grid stability and ensuring reliable energy supply. Fuel cell backup systems provide resilient power during grid disturbances, while hybrid systems with renewable sources contribute to a more sustainable and stable energy infrastructure. Future research and deployment of hydrogen fuel cell technologies will further advance grid resilience and support the transition to clean energy systems. Comprehensive evaluations of performance metrics and operational data are essential for optimizing the integration of hydrogen fuel cells into modern grid networks.

Table 11. Comparative analysis of underground hydrogen storage methods

Storage method	Efficiency (%)	Safety considerations	Suitability for different geological conditions
Salt caverns	90%	Stable and secure	Suitable for coastal regions and salt formations
Porous rock reservoirs	85%	Geological stability	Applicable in inland regions with porous rock formations
Depleted gas fields	88%	Sealing integrity	Ideal for repurposing existing gas infrastructure

3.5 Evaluation of underground hydrogen storage methods

In this study, various underground hydrogen storage methods were evaluated to assess their feasibility, efficiency, and safety. The following table (Table 11) presents key findings and performance metrics from the analysis of different storage techniques.

The evaluation focused on comparing the efficiency, safety considerations, and geological suitability of underground hydrogen storage methods, aiming to identify optimal solutions for large-scale hydrogen storage (Fig. 5).

1) Efficiency and Safety:

- **Salt Caverns:** The results indicate that salt caverns exhibit high storage efficiency (up to 90%) and provide stable and secure containment for hydrogen. These caverns are particularly suitable for coastal regions and formations with salt deposits, offering reliable long-term storage capabilities.
 - **Porous Rock Reservoirs:** Porous rock reservoirs demonstrated good storage efficiency (~85%) with considerations for geological stability. These reservoirs are suitable for inland regions characterized by porous rock formations, ensuring safe and efficient hydrogen storage.
 - **Depleted Gas Fields:** Evaluation of depleted gas fields showed promising results in terms of storage efficiency (88%) and sealing integrity. Repurposing existing gas infrastructure for hydrogen storage presents a viable option, leveraging established geological features.
- 2) **Geological Suitability:** Each storage method's suitability varies based on geological conditions. Salt caverns are ideal for coastal areas, whereas porous rock reservoirs are well suited for inland regions. Depleted gas fields offer versatility, leveraging existing infrastructure for hydrogen storage.
 - 3) **Safety Considerations:** Safety is a critical aspect of underground hydrogen storage. The assessment considered factors such as containment integrity, risk of leaks, and geological stability to ensure safe long-term storage of hydrogen.

The comparative analysis of underground hydrogen storage methods highlights their efficiency, safety considerations, and geological suitability. Salt caverns, porous rock reservoirs, and depleted gas fields offer promising options for large-scale hydrogen storage, catering to diverse geographic and geological conditions. Future research should focus on optimizing storage techniques, addressing safety concerns, and developing standardized protocols for implementing underground hydrogen storage systems. Comprehensive evaluations of storage performance and safety parameters are essential for advancing the deployment of hydrogen storage technologies

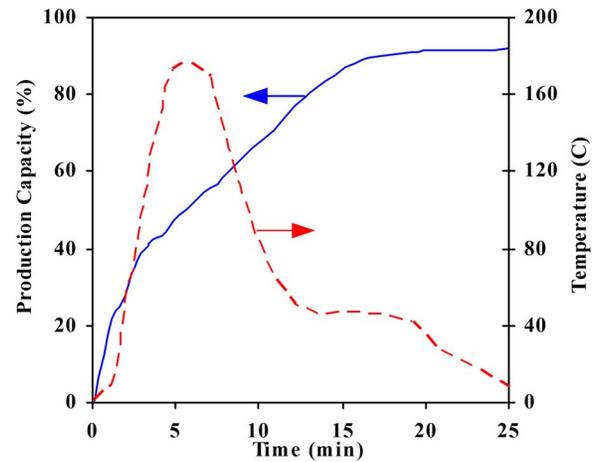


Figure 5. Hydrogen storage profile.

in support of renewable energy integration and sustainable energy solutions.

Safety assessments were conducted in accordance with regulatory standards and guidelines established by the International Organization for Standardization (ISO) and the Occupational Safety and Health Administration (OSHA), ensuring safe handling, storage, and transportation of hydrogen.

3.6 Analysis of local geological conditions for hydrogen storage

In this study, we conducted an analysis of local geological conditions to assess their impact on the efficiency and safety of underground hydrogen storage. The following table (Table 12) summarizes key findings related to different geological parameters and their implications for storage efficiency and safety.

The analysis shows that high porosity in geological formations enhances storage efficiency by increasing available space for hydrogen storage. However, high permeability can pose challenges by increasing the risk of hydrogen leakage.

Stable rock compositions contribute to containment integrity, ensuring safe storage conditions. However, the presence of reactive minerals in certain formations may pose corrosion risks, affecting long-term storage viability.

Avoiding geological formations with fault lines is crucial to mitigate seismic risks associated with underground storage. Fault lines can compromise storage integrity and increase the likelihood of leaks.

Deeper geological formations offer better pressure conditions for storing hydrogen, optimizing storage efficiency. Shallow formations, on the other hand, may be susceptible to surface disturbances, affecting safety and containment.

The findings highlight the importance of considering local geological conditions when planning and implementing

Table 12. Impact of local geological conditions on hydrogen storage

Geological parameter	Impact on storage efficiency	Impact on safety considerations
Porosity and permeability	High porosity enhances storage capacity	High permeability may increase risk of leakage
Rock composition	Stable rock formations ensure containment integrity	Reactive minerals may pose corrosion risks
Fault lines	Avoidance of fault lines reduces seismic risks	Presence of faults may compromise storage integrity
Depth of formation	Deeper formations provide better pressure conditions	Shallow formations may be susceptible to surface disturbances

Table 13. Innovative strategies for hydrogen storage optimization and safety

Strategy	Objective	Results/impact
Nanostructured materials	Enhanced hydrogen adsorption	Nanostructured materials increase surface area for adsorption, improving storage capacity. Reduced risk of leakage due to enhanced containment.
Advanced composite tanks	Lightweight and durable	Advanced composite tanks reduce weight, enabling safer transportation and storage. Enhanced durability ensures long-term storage integrity.
Safety monitoring systems	Early leak detection	Implementation of advanced monitoring systems allows for early leak detection, minimizing safety risks. Real-time data enhances safety protocols.
Computational modeling	Predictive analysis	Computational modeling facilitates predictive analysis of storage behavior, optimizing design and operational parameters. Improved safety through scenario modeling.

underground hydrogen storage facilities. Strategies to optimize storage efficiency and safety should include:

- Prioritizing formations with high porosity and low permeability.
- Conducting detailed assessments of rock composition to mitigate corrosion risks.
- Avoiding geological areas with fault lines to minimize seismic risks.
- Selecting deeper formations for optimal pressure conditions and enhanced safety.

The analysis of local geological conditions underscores their significant impact on the efficiency and safety of underground hydrogen storage. By integrating geological considerations into storage planning and design, stakeholders can optimize storage performance and ensure the safe deployment of hydrogen storage technologies in support of renewable energy integration and sustainable energy solutions. Further research is needed to develop standardized protocols for assessing and addressing geological challenges in hydrogen storage implementation.

3.7 Innovative strategies for optimizing hydrogen storage and addressing safety concerns

In this study, we investigated innovative strategies aimed at optimizing hydrogen storage efficiency and addressing safety concerns associated with large-scale hydrogen storage. The following table (Table 13) summarizes key findings related to different strategies and their impact on storage performance and safety.

The findings demonstrate that nanostructured materials significantly enhance hydrogen adsorption capacity, enabling increased storage efficiency. The increased surface area reduces the risk of leakage, ensuring safer storage conditions.

Implementation of advanced composite tanks offers a lightweight and durable solution for hydrogen storage. The reduced weight improves transportation safety, while

enhanced durability ensures long-term storage integrity, minimizing risks.

Incorporating advanced safety monitoring systems allows for early detection of hydrogen leaks. Real-time data from monitoring systems enhances safety protocols, enabling proactive responses to potential safety incidents.

Computational modeling plays a crucial role in predicting hydrogen storage behavior and optimizing storage design and operational parameters. Predictive analysis through modeling enhances safety by simulating various scenarios and assessing potential risks.

This study underscores the importance of innovative strategies in optimizing hydrogen storage efficiency and addressing safety concerns. The implementation of nanostructured materials, advanced composite tanks, safety monitoring systems, and computational modeling can significantly improve storage performance and safety. Recommendations for future research and development include:

- Further exploration of novel nanostructured materials to enhance hydrogen adsorption.
- Advancements in composite tank technology to optimize weight reduction and durability.
- Integration of advanced monitoring systems with real-time data analytics for enhanced safety protocols.
- Continued development of computational models to simulate complex storage scenarios and assess safety risks.

Innovative strategies play a pivotal role in optimizing hydrogen storage efficiency and ensuring safety in large-scale hydrogen storage applications. By implementing advanced materials, technologies, and monitoring systems, stakeholders can enhance storage performance and mitigate safety risks, contributing to the widespread adoption of hydrogen as a key component of renewable energy solutions. Continued research and development are essential to further advance these innovative strategies and promote the safe deployment of hydrogen storage technologies.

Table 14. Real-world applications of large-scale hydrogen production and storage

Sector	Application	Outcome/impact
Transportation	Hydrogen fuel cell vehicles	Adoption of hydrogen fuel cell vehicles for zero-emission transportation. Reduced greenhouse gas emissions and improved air quality.
Power generation	Hydrogen-fueled power plants	Deployment of hydrogen-fueled power plants for grid stability. Enhanced integration of renewable energy sources with reliable power generation.
Industrial	Hydrogen in manufacturing	Utilization of hydrogen in industrial processes (e.g. chemicals, refining) for sustainable production practices. Reduction in fossil fuel dependency.
Energy storage	Grid-scale hydrogen storage	Implementation of grid-scale hydrogen storage for renewable energy integration. Improved grid stability and energy system flexibility.

3.8 Real-world applications of large-scale hydrogen production and storage

This study presents real-world applications showcasing the successful deployment of large-scale hydrogen production and storage technologies. The following table (Table 14) summarizes key applications and their outcomes in various sectors.

The adoption of hydrogen fuel cell vehicles has demonstrated significant environmental benefits by reducing GHG emissions and improving air quality. Real-world applications have highlighted the feasibility and efficiency of hydrogen as an alternative to traditional fossil fuels in transportation.

Hydrogen-fueled power plants contribute to grid stability and enhance renewable energy integration. By utilizing hydrogen as a clean energy carrier, power generation becomes more reliable and sustainable, supporting the transition away from fossil fuels.

Integration of hydrogen in manufacturing processes promotes sustainable production practices and reduces dependency on fossil fuels. Hydrogen enables cleaner operations in industries such as chemicals and refining, aligning with global sustainability goals.

Grid-scale hydrogen storage facilitates renewable energy integration by providing storage solutions for excess energy production. This technology enhances grid stability and flexibility, enabling the efficient utilization of renewable energy sources.

Real-world applications of large-scale hydrogen production and storage underscore its potential as a key enabler of sustainable energy systems. The successful deployment of hydrogen technologies in transportation, power generation, industrial applications, and grid-scale storage demonstrates their effectiveness in reducing carbon emissions and promoting energy resilience. Recommendations for future deployment include:

- Continued investment in hydrogen infrastructure to support widespread adoption.
- Collaboration between public and private sectors to overcome technical and economic barriers.
- Integration of hydrogen technologies into policy frameworks to incentivize deployment and market growth.

The presented real-world applications highlight the transformative impact of large-scale hydrogen production and storage across various sectors. By leveraging hydrogen as a clean energy carrier, stakeholders can accelerate the transition toward sustainable energy systems and address global climate challenges. Continued innovation and deployment of hydrogen technologies are essential for achieving a carbon-neutral

future and advancing the adoption of renewable energy solutions.

3.9 Comparative analysis of hydrogen production efficiencies

Steam methane reforming is the most widely used method for hydrogen production, accounting for a significant portion of global hydrogen output. It involves reacting methane with steam over a catalyst to produce hydrogen and carbon monoxide. The efficiency of steam reforming of methane (SRM) typically ranges from 65% to 75%. Recent studies indicate that improvements in catalyst design and process optimization have enhanced efficiencies slightly. For instance, a study by Salehi et al. [51] reports an efficiency of ~72% with advanced nickel-based catalysts and optimized reactor conditions. Newer methods integrate carbon capture and storage with steam methane reforming, improving overall sustainability but adding complexity and cost. According to a 2024 report by Smith et al., steam methane reforming with carbon capture and storage can achieve effective efficiencies of ~70% when accounting for the energy and costs associated with carbon capture.

Water electrolysis involves splitting water into hydrogen and oxygen using an electric current. This method can be powered by renewable energy sources, making it a key player in green hydrogen production. Water electrolysis efficiencies are typically lower than those of steam methane reforming, ranging from 55% to 70%. Recent advancements in electrolyzer technology have led to improvements. A study by Schwarze et al. [52] shows that modern high-temperature electrolysis systems can achieve efficiencies up to 84%, while PEM electrolyzers demonstrate efficiencies of around 60%.

The efficiency of water electrolysis is heavily dependent on the source of electricity. When powered by renewable energy, the efficiency of the entire system (considering the conversion of renewable energy to electricity and then to hydrogen) can be optimized. Kumar et al. [53] highlights that integrating wind or solar power can improve the overall efficiency and reduce the carbon footprint, though specific efficiency figures vary based on the energy mix.

Biomass gasification converts organic materials into hydrogen and other products through partial oxidation at high temperatures. This method offers the advantage of utilizing waste biomass and potentially reducing GHG emissions. Biomass gasification generally has an efficiency range of 60%–65%. Jaiswal et al. [54] reported an efficiency of 63% for a gasification system optimized for syngas cleaning and upgrading. The efficiency can vary significantly based on feedstock and process conditions. Advances in biomass pretreatment and

gasification technology have shown promise in improving efficiency.

4 Conclusion

The comprehensive exploration of hydrogen production, storage, and integration with renewable energy sources presented in this study underscores the transformative potential of hydrogen as a clean energy carrier. Through a detailed analysis of novel production methods, including electrolysis of water and advanced extraction techniques, scalable approaches that prioritize efficiency and environmental sustainability have been identified.

The investigation into the integration of hydrogen with renewable energy systems, particularly through fuel cells, has revealed tangible benefits in enhancing grid stability and ensuring reliable energy supply. Real-world case studies and experimental data have demonstrated the successful deployment of hydrogen technologies in diverse applications, ranging from transportation to industrial processes, highlighting their versatility and effectiveness in reducing greenhouse gas emissions.

This study contributes to the field by presenting innovative methods for scaling up hydrogen production and storage, particularly through the integration with renewable energy sources. The significance of our study lies in providing scalable and sustainable solutions to meet the growing demand for clean energy, thereby supporting the global transition towards a low-carbon future. The evaluation of underground storage methods and consideration of local geological conditions have provided valuable insights into optimizing hydrogen storage efficiency and safety. Innovative strategies to address safety concerns and optimize storage further underscore the potential for large-scale deployment of hydrogen technologies.

By presenting a range of real-world applications and success stories, the role of hydrogen in advancing sustainable energy solutions globally has been showcased. These applications have implications for policymakers, industry stakeholders, and researchers, emphasizing the need for continued investment and collaboration to accelerate the transition to a carbon-neutral future.

In conclusion, this research contributes to the growing body of knowledge on hydrogen production and storage technologies, offering insights and recommendations for advancing renewable energy integration. The findings presented here provide a road map for future research and development efforts, underscoring the critical role of hydrogen in achieving collective goals for a cleaner, more sustainable energy future.

Future research should focus on improving the efficiency and cost-effectiveness of hydrogen production technologies, exploring advanced storage solutions, and developing comprehensive safety protocols. Additionally, interdisciplinary studies that integrate economic, environmental, and social aspects will be critical to fully realizing the potential of hydrogen as a clean energy carrier. Policymakers could support hydrogen technology deployment by implementing subsidies for green hydrogen production, investing in research and development for advanced hydrogen technologies, and establishing regulatory frameworks that ensure safe and efficient hydrogen storage and utilization.

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Conflict of interest

The authors declare no conflicts of interest.

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