



Hydrogen-Based Renewable Energy Systems: Technologies, Challenges, and Future Prospects for Sustainable Energy

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Abstract

The increasing demand for clean, reliable, and sustainable energy has accelerated the adoption of hydrogen-based renewable energy systems as a key solution for achieving carbon neutrality. Green hydrogen, produced through water electrolysis powered by renewable energy sources such as solar and wind, offers a clean energy carrier with zero carbon emissions during utilization. Hydrogen can be stored for extended periods, transported efficiently, and converted back into electricity through fuel cells, making it an effective solution for addressing the intermittency of renewable energy sources. This paper presents a comprehensive review of hydrogen production technologies, storage methods, fuel cell systems, and their integration with renewable energy resources. It also discusses the role of hydrogen in smart grids, transportation, industrial applications, and microgrids. Furthermore, recent advancements involving artificial intelligence (AI), the Internet of Things (IoT), and digital twins for hydrogen energy management are reviewed. Finally, the paper highlights existing challenges, future research directions, and opportunities for large-scale commercialization.

Keywords: Green Hydrogen, Renewable Energy, Electrolysis, Fuel Cell, Hydrogen Storage, Smart Grid, Artificial Intelligence, Microgrid, Energy Management.

1. Introduction

Hydrogen-based renewable energy systems have emerged as one of the most promising solutions for achieving a sustainable, low-carbon, and energy-secure future. As global energy demand continues to rise and concerns over climate change intensify, the transition from fossil fuel-based energy sources to renewable alternatives has become a critical priority. Renewable energy resources such as solar, wind, hydroelectric, and biomass offer clean electricity generation but are inherently intermittent, creating challenges in energy storage and grid stability. Hydrogen serves as an effective energy carrier capable of storing surplus renewable energy through electrolysis and supplying it when demand exceeds generation. Green hydrogen, produced using

renewable electricity, offers zero-carbon emissions during production and utilization, making it an attractive option for decarbonizing sectors such as transportation, power generation, industrial manufacturing, and residential energy systems. Recent technological advancements in electrolyzers, fuel cells, hydrogen storage materials, and integrated renewable energy systems have significantly improved the feasibility and efficiency of hydrogen-based energy solutions. Despite these developments, several technical, economic, and infrastructural challenges continue to limit their large-scale commercialization, including high production costs, storage and transportation complexities, efficiency losses, and the need for extensive hydrogen

distribution networks. Furthermore, policy support, safety regulations, and investments in research and development are essential to accelerate hydrogen adoption worldwide [1]. This paper presents a comprehensive review of hydrogen-based renewable energy systems by examining current production technologies, storage methods, conversion techniques, and practical applications. It also discusses the major challenges facing hydrogen deployment and explores future prospects, highlighting innovative technologies, policy initiatives, and research directions that can facilitate the widespread adoption of hydrogen as a cornerstone of sustainable global energy systems Shown in Figure 1.

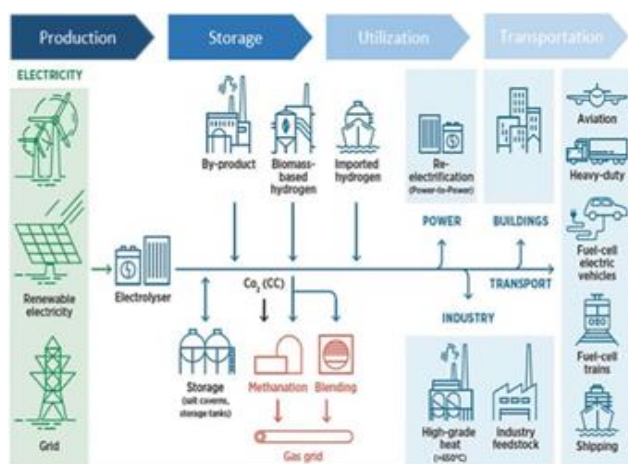


Figure 1 Integrated Green Hydrogen Energy System Pathway

2. Literature Survey

Hydrogen-based renewable energy systems have emerged as a promising solution for achieving carbon neutrality and enhancing global energy security. Green hydrogen, produced through water electrolysis powered by renewable energy sources such as solar, wind, and hydropower, is gaining considerable attention due to its potential to decarbonize sectors that are difficult to electrify, including heavy industry, transportation, and long-term energy storage. Numerous researchers have investigated hydrogen production technologies, storage methods, fuel cell applications, and system integration

strategies to improve overall efficiency and economic feasibility. Turner (2004) highlighted hydrogen as a clean energy carrier capable of replacing fossil fuels in future energy systems. The study emphasized that hydrogen produced using renewable electricity can significantly reduce greenhouse gas emissions while supporting sustainable energy development. However, the research also identified the high cost of hydrogen production and storage as major barriers to commercialization. Staffell et al. (2019) conducted a comprehensive review of hydrogen and fuel cell technologies, demonstrating that renewable hydrogen offers substantial environmental benefits compared with conventional fossil fuel-based hydrogen production. The authors reported that advances in proton exchange membrane (PEM) electrolyzers and solid oxide electrolyzers have improved energy conversion efficiencies, making green hydrogen increasingly competitive for industrial applications. IRENA (2020) reported that declining costs of renewable electricity and electrolyzer technologies are expected to accelerate the global adoption of green hydrogen. The report predicted that hydrogen would become an essential component of future integrated energy systems by enabling seasonal energy storage, balancing intermittent renewable power generation, and supporting decarbonization across multiple sectors. Glenk and Reichelstein (2019) analyzed the economics of green hydrogen production and concluded that electricity prices remain the dominant factor influencing hydrogen production costs. Their research suggested that countries with abundant renewable energy resources possess a competitive advantage in large-scale green hydrogen generation. The study also emphasized the importance of government incentives and supportive policies to improve market competitiveness. Carmo et al. (2013) reviewed water electrolysis technologies, including alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOEC). The authors compared system efficiencies, operating conditions, durability, and capital costs, concluding that PEM electrolyzers offer superior dynamic response suitable for

renewable energy integration, while SOEC systems provide higher efficiencies at elevated temperatures. Dawood et al. (2020) investigated hydrogen production, storage, transportation, and utilization technologies, emphasizing the need for integrated hydrogen infrastructure. Their review highlighted compressed gas storage, liquefied hydrogen, and metal hydrides as the primary storage techniques, each with specific advantages and technical limitations. Safety concerns and infrastructure development were identified as critical research priorities. Ajanovic and Haas (2021) examined the role of hydrogen in achieving global climate neutrality. Their analysis indicated that green hydrogen could significantly reduce carbon emissions in steel manufacturing, chemical industries, and heavy-duty transportation. However, the authors emphasized that widespread deployment depends on reducing electrolyzer costs and increasing renewable electricity generation capacity. IEA (2023) reported that global investments in hydrogen technologies have increased substantially due to supportive governmental policies and international decarbonization initiatives. The report highlighted rapid advancements in large-scale electrolyzer manufacturing, hydrogen transportation networks, and fuel cell deployment while stressing that infrastructure expansion and regulatory standardization remain significant challenges. Recent studies have also explored artificial intelligence (AI) and Internet of Things (IoT) technologies for optimizing hydrogen energy systems. AI-based energy management techniques improve electrolyzer operation, predict hydrogen demand, and optimize renewable power utilization. IoT-enabled monitoring systems facilitate real-time performance analysis, fault detection, and predictive maintenance, thereby improving system reliability and operational efficiency. Despite significant technological progress, several challenges remain before hydrogen-based renewable energy systems can be widely adopted. High capital investment, limited storage capacity, transportation difficulties, safety concerns, low round-trip efficiency, and inadequate

infrastructure continue to hinder commercialization. Future research focuses on developing high-efficiency electrolyzers, advanced hydrogen storage materials, smart energy management systems, and integrated renewable-hydrogen power networks. The literature indicates that combining renewable energy technologies with hydrogen production, supported by digital technologies such as AI and IoT, will play a pivotal role in building sustainable, resilient, and carbon-neutral energy systems [2].

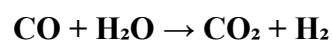
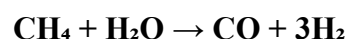
3. Hydrogen Production Technologies

Hydrogen production technologies are central to the development of a sustainable hydrogen economy, enabling the transition from fossil fuel-based energy systems to low-carbon and renewable energy solutions. Depending on the energy source and production process, hydrogen can be classified into different categories such as grey, blue, green, turquoise, pink, and white hydrogen. Each production technology has unique advantages, limitations, efficiency levels, environmental impacts, and economic considerations. The selection of an appropriate hydrogen production method depends on factors including resource availability, carbon emissions, production cost, scalability, and end-use applications.

3.1. Steam Methane Reforming (SMR)

Steam Methane Reforming is the most widely used commercial method for hydrogen production, accounting for nearly 70–75% of global hydrogen production. In this process, natural gas reacts with high-temperature steam (700–1,000°C) in the presence of a nickel catalyst to produce hydrogen and carbon monoxide. The carbon monoxide is further converted into carbon dioxide and additional hydrogen through the water-gas shift reaction.

Chemical Reactions:



Advantages:

- Mature and commercially established

technology

- High hydrogen production efficiency (65–75%)
- Relatively low production cost
- Large-scale industrial implementation

Disadvantages:

- Significant CO₂ emissions
- Dependence on fossil fuels
- Environmental concerns due to greenhouse gas emissions [3]

3.2. Coal Gasification

Coal gasification converts coal into synthesis gas (syngas) consisting mainly of hydrogen, carbon monoxide, and carbon dioxide by reacting coal with steam and oxygen at high temperatures Shown in Figure 2.

Advantages:

- Utilizes abundant coal resources
- Suitable for large-scale hydrogen production
- Established industrial technology

Disadvantages:

- Highest carbon emissions among hydrogen production methods
- High water consumption
- Environmental pollution
- Carbon capture is essential for sustainability

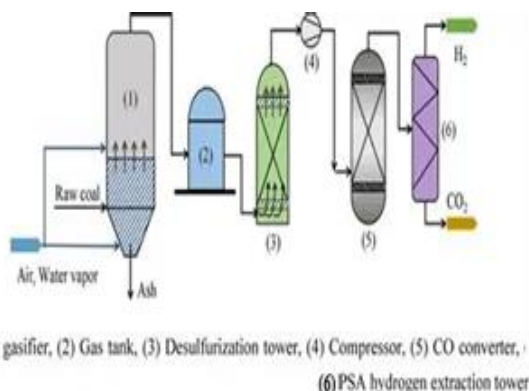


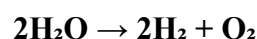
Figure 2 Integrated Coal Gasification and Hydrogen Extraction Process Flow Diagram

3.3. Water Electrolysis

Water electrolysis is considered one of the cleanest hydrogen production methods when powered by

renewable electricity. It separates water into hydrogen and oxygen using an electric current.

Overall Reaction:



3.4. Types of Electrolyzers

3.4.1. Alkaline Electrolysis (AEL)

- Uses potassium hydroxide (KOH) or sodium hydroxide (NaOH) electrolyte
- Commercially mature technology
- Efficiency: 60–70%

Advantages

- Low capital cost
- Long operational lifetime
- Proven reliability

Limitations

- Lower current density
- Slow dynamic response

3.4.2. Proton Exchange Membrane (PEM) Electrolysis

PEM electrolyzers use a solid polymer membrane and operate efficiently with renewable energy sources.

Efficiency: 65–80%

Advantages

- High hydrogen purity
- Compact system
- Fast response to fluctuating renewable energy

Limitations

- High catalyst cost (platinum, iridium)
- Expensive membrane materials

3.4.3. Solid Oxide Electrolysis Cells (SOEC)

SOEC operates at temperatures between 700°C and 900°C using ceramic electrolytes Shown in Figure 3.

Efficiency: 80–90%

Advantages

- Highest electrical efficiency
- Reduced electricity consumption
- Suitable for industrial waste heat utilization

Limitations

- High operating temperature
- Material degradation [4]
- Limited commercial deployment

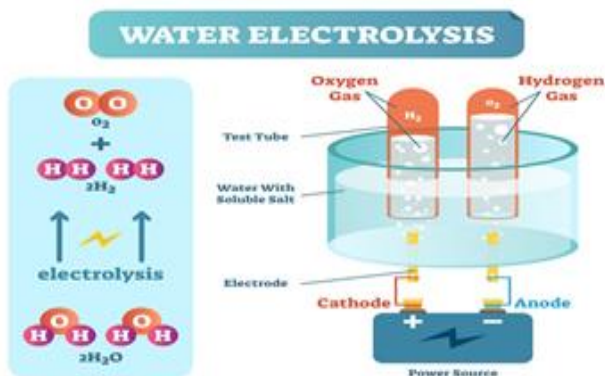


Figure 3 Water Electrolysis Process for Green Hydrogen Generation

4. Biomass Gasification

Biomass gasification is a thermochemical process that converts carbonaceous solid fuels into a gaseous energy medium primarily composed of carbon monoxide (CO) and hydrogen (H₂) Shown in Figure 4.

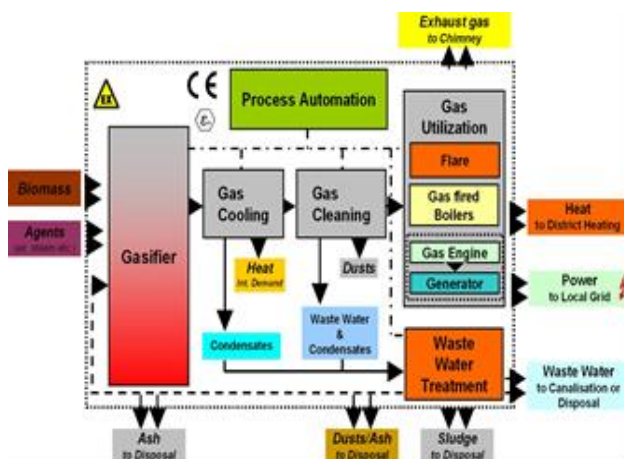


Figure 4 Biomass-to-Energy Conversion Process through Gasification Technology

This process involves several stages: drying the biomass particles, pyrolysis, partial oxidation, and char gasification. The gasification process is

recognized for its ability to produce syngas, which can be used for various applications, including heating, electricity generation, and biofuel production. Biomass gasification is considered one of the most effective methods for energy recovery from biomass, offering a sustainable and renewable energy resource.

5. Biological Hydrogen Production

Biological hydrogen production is an emerging and environmentally friendly approach for generating hydrogen using microorganisms such as algae, cyanobacteria, and photosynthetic or fermentative bacteria. Unlike conventional hydrogen production methods that rely on fossil fuels, biological processes utilize renewable feedstocks, including agricultural residues, wastewater, and organic biomass, making them a sustainable alternative for clean energy generation. The two primary biological pathways are photo-biological hydrogen production, which uses sunlight as the energy source, and dark fermentation, where anaerobic bacteria convert organic substrates into hydrogen without the need for light. Other promising methods, such as photo-fermentation and bio photolysis, employ specialized microorganisms to enhance hydrogen production through metabolic and photosynthetic processes. These technologies operate under mild temperatures and pressures, consume fewer non-renewable resources, and contribute to reducing greenhouse gas emissions, aligning well with global carbon neutrality goals Shown in Figure 5.

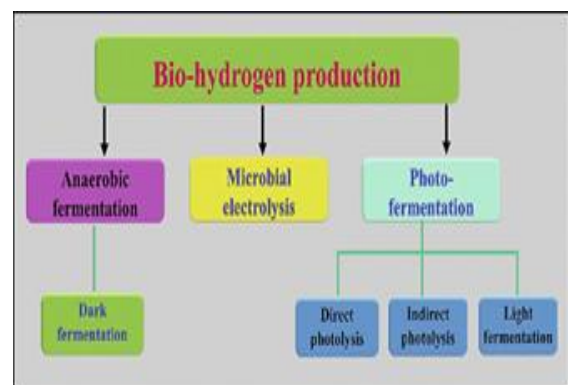


Figure 5 Different Biological Routes for Bio-hydrogen Production



6. Thermochemical Water Splitting

Thermochemical water splitting is an advanced and sustainable hydrogen production technology that generates hydrogen by decomposing water through a sequence of high-temperature chemical reactions. Unlike conventional electrolysis, which requires large amounts of electricity, thermochemical water splitting primarily utilizes thermal energy obtained from concentrated solar power (CSP), high-temperature nuclear reactors, or industrial waste heat. The process involves multiple intermediate chemical reactions that split water into hydrogen and oxygen without the direct use of electricity, thereby improving overall energy efficiency. Among the most widely studied thermochemical cycles are the Sulfur-Iodine (S-I) cycle and the Copper-Chlorine (Cu-Cl) cycle, both of which have demonstrated significant potential for large-scale hydrogen production with minimal greenhouse gas emissions. Thermochemical water splitting offers several advantages, including high hydrogen production efficiency, reduced dependence on fossil fuels, and compatibility with renewable and nuclear energy sources. Since the process does not emit carbon dioxide during hydrogen generation, it is considered a promising pathway for producing green hydrogen and supporting global decarbonization efforts. However, widespread commercialization faces several challenges, such as the requirement for extremely high operating temperatures (typically above 800°C), corrosion-resistant materials, complex reactor designs, and high initial investment costs. Ongoing research focuses on developing durable materials, improving reaction efficiency, and integrating thermochemical cycles with renewable energy systems. These advancements are expected to enhance the economic feasibility and scalability of thermochemical water splitting, making it a vital technology for future sustainable hydrogen production [5].

7. Hydrogen Storage Technologies

Hydrogen storage is a critical component of the hydrogen energy value chain, enabling the safe, efficient, and reliable transportation and utilization of

hydrogen in various applications. Due to its low volumetric energy density under ambient conditions, hydrogen requires specialized storage methods that improve its energy density while ensuring safety and minimizing energy losses. Hydrogen storage technologies are broadly classified into physical storage methods and material-based storage methods. The major storage technologies are described below.

7.1. Compressed Gaseous Hydrogen Storage (CGH₂)

Compressed gaseous hydrogen storage is the most widely adopted and commercially mature hydrogen storage technology. In this method, hydrogen gas is stored in high-pressure cylinders or tanks at pressures ranging from 350 bar to 700 bar. Modern storage tanks are typically manufactured from lightweight carbon fiber-reinforced composite materials, offering high strength, corrosion resistance, and enhanced safety. This technology is extensively used in fuel cell electric vehicles (FCEVs), hydrogen refueling stations, and industrial applications due to its relatively simple design and rapid charging capability. The main advantages include technological maturity, fast filling and discharge, and compatibility with existing hydrogen infrastructure. However, compressed storage has a relatively low volumetric energy density compared to liquid hydrogen, requiring large storage volumes for substantial hydrogen quantities. In addition, the compression process consumes significant energy, and the storage tanks are expensive because of their advanced composite construction. Despite these challenges, continuous improvements in tank materials and compression technologies are enhancing storage efficiency and reducing costs.

7.2. Liquid Hydrogen Storage (LH₂)

Liquid hydrogen storage involves cooling hydrogen to its boiling point of approximately -253°C, where it condenses into a cryogenic liquid. This method significantly increases the volumetric energy density compared to compressed gas storage, making it suitable for aerospace applications, long-distance transportation, and large-scale hydrogen distribution. Liquid hydrogen is stored in highly insulated



cryogenic tanks designed to minimize heat transfer and reduce evaporation losses. The technology offers compact storage, enabling greater quantities of hydrogen to be transported within smaller volumes. However, the liquefaction process is energy-intensive, consuming approximately 30–40% of the energy contained in the hydrogen itself. Furthermore, hydrogen boil-off during storage and transportation results in fuel losses and increases operational costs. Maintaining extremely low temperatures also requires sophisticated insulation systems and specialized handling procedures. Ongoing research focuses on improving cryogenic insulation materials and reducing liquefaction energy requirements to enhance the commercial viability of liquid hydrogen storage [6].

7.3.Metal Hydride Storage

Metal hydride storage is a material-based hydrogen storage technology in which hydrogen is chemically absorbed into metals or metal alloys to form stable metal hydrides. Common storage materials include magnesium hydride, lanthanum-nickel alloys, titanium-based alloys, and sodium alanate. Hydrogen is released when the hydride material is heated under controlled conditions. This technology offers excellent volumetric hydrogen density, low operating pressure, and enhanced safety due to the chemical bonding of hydrogen within the storage material. Metal hydride systems are particularly attractive for stationary energy storage, backup power systems, and portable fuel cell applications. However, they generally possess a relatively high system weight, making them less suitable for transportation applications. Additionally, slow hydrogen absorption and desorption kinetics, high material costs, and thermal management requirements limit their widespread adoption. Current research aims to develop lightweight hydride materials with faster hydrogen release rates and improved storage capacities, making metal hydride storage more efficient and commercially practical.

7.4.Chemical Hydrogen Storage

Chemical hydrogen storage stores hydrogen within chemical compounds such as ammonia (NH_3),

methanol (CH_3OH), formic acid, and liquid organic hydrogen carriers (LOHCs). Hydrogen is released through catalytic decomposition or chemical reforming when required for energy applications. This approach enables high hydrogen storage density while allowing the use of existing fuel transportation and distribution infrastructure. Ammonia is particularly attractive because it contains approximately 17.6% hydrogen by weight and can be transported using well-established industrial systems. Chemical storage offers excellent long-term storage capability and simplified transportation compared to compressed or liquid hydrogen. However, hydrogen extraction requires additional processing, catalysts, and energy input, increasing system complexity and operational costs. Some storage compounds may also produce by-products that require further treatment. Research efforts are focused on developing highly efficient catalysts, reversible storage materials, and low-temperature hydrogen release technologies to improve the overall efficiency and sustainability of chemical hydrogen storage systems.

7.5.Liquid Organic Hydrogen Carriers (LOHCs)

Liquid Organic Hydrogen Carriers are organic compounds capable of reversibly absorbing and releasing hydrogen through catalytic hydrogenation and dehydrogenation reactions. Common LOHC materials include toluene/methylcyclohexane and dibenzyltoluene systems. One of the major advantages of LOHC technology is that these liquids remain stable under ambient temperature and pressure, allowing hydrogen to be stored and transported using conventional fuel infrastructure such as pipelines, storage tanks, and tanker trucks. LOHC systems provide high safety, low hydrogen losses, and long-term storage capability without requiring high-pressure cylinders or cryogenic temperatures. However, hydrogen release requires elevated temperatures and efficient catalysts, increasing energy consumption and system cost. Catalyst degradation and incomplete hydrogen release are additional technical challenges. Ongoing research is directed toward improving catalyst

performance, reducing dehydrogenation temperatures, and identifying new carrier molecules with higher hydrogen capacities and better cycling stability for commercial hydrogen energy systems.

7.6. Carbon-Based Hydrogen Storage

Carbon-based hydrogen storage utilizes porous carbon materials such as activated carbon, carbon nanotubes (CNTs), graphene, and carbon nanofibers to adsorb hydrogen molecules onto their large surface areas. Hydrogen is stored primarily through physical adsorption, particularly at low temperatures and elevated pressures. Carbon nanomaterials offer several advantages, including lightweight construction, high specific surface area, excellent mechanical strength, and rapid hydrogen charging and discharging characteristics. They also exhibit superior chemical stability and long operational life. Despite these benefits, the hydrogen storage capacity of many carbon materials under ambient conditions remains relatively low, limiting commercial applications. Achieving higher storage capacities often requires cryogenic temperatures or high-pressure conditions, increasing system complexity. Researchers continue to investigate nanostructured carbon materials, surface modifications, and hybrid composites to improve hydrogen adsorption performance. These advancements may enable carbon-based materials to become viable storage solutions for portable electronics, fuel cell vehicles, and renewable energy storage [7] [8].

8. Integration with Renewable Energy Systems

The integration of hydrogen with renewable energy systems has emerged as a key strategy for achieving a reliable, sustainable, and low-carbon energy infrastructure. Renewable energy sources such as solar photovoltaic (PV), wind, and hydropower are inherently intermittent, with electricity generation depending on weather conditions and seasonal variations. This intermittency creates challenges in balancing electricity supply and demand, often leading to excess power generation during periods of high renewable output and energy shortages during periods of low generation. Hydrogen provides an effective solution by acting as a long-duration energy

storage medium. Surplus renewable electricity can be converted into hydrogen through water electrolysis, producing green hydrogen without greenhouse gas emissions. The generated hydrogen can then be stored for extended periods and converted back into electricity using fuel cells or gas turbines whenever renewable power generation is insufficient. Hydrogen-based energy storage significantly enhances grid flexibility, stability, and reliability while enabling greater penetration of renewable energy sources into modern power systems. Unlike conventional battery storage, which is generally suitable for short-duration applications, hydrogen can store large amounts of energy for weeks or even months, making it ideal for seasonal energy storage and large-scale grid balancing. In addition to electricity generation, stored hydrogen can be utilized in transportation, industrial manufacturing, residential heating, and chemical production, thereby creating an integrated energy ecosystem that links the power, transport, and industrial sectors. This sector coupling improves overall energy efficiency and reduces dependence on fossil fuels. Recent advancements in electrolyzer technologies, fuel cells, smart grid control, artificial intelligence-based energy management, and hydrogen storage systems have further strengthened the feasibility of renewable hydrogen integration. Governments and industries worldwide are investing in green hydrogen infrastructure, including hydrogen production plants, storage facilities, pipelines, and refueling stations, to accelerate the transition toward carbon-neutral energy systems. Although challenges such as high production costs, infrastructure development, and energy conversion losses remain, continuous technological innovations and supportive policy frameworks are expected to improve economic viability. Consequently, the integration of hydrogen with renewable energy systems is recognized as a cornerstone of the future clean energy economy, supporting global decarbonization, energy security, and sustainable development.

Conclusion

Hydrogen-based renewable energy systems have



emerged as a promising solution for addressing the growing global demand for clean, reliable, and sustainable energy while supporting the transition toward a low-carbon economy. Green hydrogen, produced through renewable-powered water electrolysis, offers a carbon-free energy carrier that can overcome the intermittency of renewable energy sources such as solar and wind. Advances in hydrogen production technologies, including alkaline, proton exchange membrane (PEM), and solid oxide electrolysis, along with improvements in storage methods such as compressed gas, liquid hydrogen, metal hydrides, and chemical carriers, have significantly enhanced the practicality of hydrogen as a long-term energy storage medium. Furthermore, the integration of hydrogen with renewable energy systems enables efficient utilization of surplus electricity, improves grid stability, and supports the decarbonization of transportation, industrial processes, and power generation. Despite these significant advantages, several technical, economic, and infrastructural challenges continue to hinder the widespread commercialization of hydrogen-based energy systems. High production costs, limited hydrogen storage capacity, transportation complexities, material durability issues, and the lack of comprehensive refueling and distribution infrastructure remain major barriers to large-scale adoption. In addition, improving electrolyzer efficiency, reducing catalyst costs, enhancing storage safety, and minimizing energy losses during hydrogen conversion are critical research priorities. Addressing these challenges will require continued innovation in materials science, electrochemical engineering, and system integration, supported by coordinated government policies, international collaboration, and private-sector investment.

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