



Green Hydrogen as an Alternative Energy Source for Improving Sustainability: Opportunities, Challenges and Future Perspectives

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Abstract

The rapid depletion of fossil fuel reserves, increasing greenhouse gas emissions, and global commitments toward carbon neutrality have accelerated the search for sustainable alternative energy sources. Among the available clean energy carriers, green hydrogen has emerged as one of the most promising solutions due to its ability to store renewable energy, decarbonize energy-intensive industries, and improve long-term energy security. Unlike conventional hydrogen, green hydrogen is produced through water electrolysis using renewable electricity, resulting in negligible carbon emissions during production. This paper reviews the role of green hydrogen in improving environmental, economic, and social sustainability by examining recent developments in production technologies, industrial applications, policy initiatives, and commercialization challenges. The study further discusses technological limitations, infrastructure requirements, and future research opportunities associated with large-scale hydrogen deployment. The findings indicate that declining renewable energy costs, improvements in electrolyzer technologies, and supportive government policies will significantly enhance the feasibility of green hydrogen as a sustainable alternative to fossil fuels. The paper concludes that green hydrogen has the potential to become a cornerstone of future low-carbon energy systems and contribute substantially toward achieving

global climate goals and sustainable development.

Keywords: Green hydrogen, Renewable energy, Sustainability, Energy transition, Carbon neutrality, Water electrolysis, Hydrogen economy.



1. Introduction

The global energy sector is undergoing a major transformation driven by increasing energy demand, environmental degradation, climate change, and the urgent need to reduce dependence on fossil fuels. Conventional energy resources such as coal, petroleum, and natural gas continue to supply the majority of the world's primary energy demand; however, their extensive utilization has resulted in significant greenhouse gas emissions, air pollution, ecological degradation, and growing concerns regarding long-term energy security [1,2]. According to recent international energy assessments, achieving global carbon neutrality requires a rapid transition toward renewable and low-carbon energy systems capable of meeting future energy demands while minimizing environmental impacts [1].

Renewable energy technologies including solar photovoltaic, wind power, hydropower, biomass, and geothermal energy have experienced remarkable growth during the past decade. Nevertheless, the intermittent nature of renewable electricity generation remains one of the principal challenges limiting their large-scale integration into modern power systems. The variability associated with solar irradiation and wind speed necessitates efficient long-duration energy storage technologies capable of balancing electricity generation and consumption [2,3]. In this context, hydrogen has emerged as an attractive energy carrier because of its high gravimetric energy density, flexibility, and ability to store renewable energy over extended periods.

Hydrogen can be produced through several production pathways including steam methane reforming, coal gasification, biomass conversion, thermochemical processes, and water electrolysis. Depending on the production route, hydrogen is generally classified as grey, blue, turquoise, pink, and green hydrogen. Among these alternatives, green hydrogen is considered the most environmentally sustainable because it is generated through the electrolysis of water using electricity obtained entirely from renewable energy sources. Since the production process does not involve fossil fuel combustion, greenhouse gas emissions associated with green hydrogen are almost negligible, making it an attractive solution for achieving global decarbonization targets [3,4].

The versatility of green hydrogen has attracted considerable interest from governments, researchers, and industries worldwide. Green hydrogen can serve as an alternative fuel for transportation, power generation, steel manufacturing, chemical processing, petroleum refining, fertilizer production, and long-term energy storage. Unlike battery storage systems, hydrogen enables seasonal energy storage and facilitates the utilization of surplus renewable electricity generated during periods of high solar or wind availability. Consequently, hydrogen is increasingly recognized as an essential component of future integrated renewable energy systems capable of improving grid stability and energy resilience [4,5].

Several countries have already formulated national hydrogen strategies to accelerate research, infrastructure development, and industrial commercialization. The European Union, Japan, Australia, Germany, the United States, China, and India have announced ambitious investment programs supporting hydrogen production, transportation, storage, and utilization. India launched the National Green Hydrogen Mission with the objective of producing approximately five million metric tonnes of green hydrogen annually by 2030 while reducing fossil fuel imports, strengthening domestic manufacturing, generating employment opportunities, and supporting the country's commitment to achieve net-zero greenhouse gas emissions by 2070 [6].

Recent sustainability studies have demonstrated that successful energy transition requires comprehensive assessment frameworks that simultaneously evaluate environmental performance, energy efficiency, economic feasibility, technological advancement, and policy effectiveness. Jena et al. developed the Madhab's Environmental-Efficiency-Economic (EEE) Impact Model to evaluate alternative energy systems and



demonstrated that renewable energy technologies significantly outperform conventional fossil fuel-based energy sources from sustainability and economic perspectives [7]. In another investigation, Jena et al. evaluated the environmental impacts of conventional manufacturing systems and highlighted the importance of renewable energy integration and green manufacturing practices for reducing industrial emissions and improving sustainability performance [8]. Furthermore, Jena et al. reported that the application of artificial intelligence and advanced digital technologies can substantially improve energy efficiency, operational reliability, and environmental sustainability in manufacturing industries, thereby supporting future renewable energy integration [9]. These multidimensional studies indicate that technological innovation and integrated sustainability assessment frameworks will play a critical role in accelerating the adoption of emerging clean energy technologies such as green hydrogen.

Despite considerable technological progress, several challenges continue to limit the widespread commercialization of green hydrogen. High electrolyzer costs, substantial renewable electricity requirements, hydrogen storage and transportation constraints, infrastructure deficiencies, and policy uncertainties remain significant barriers to large-scale deployment [3,5]. In addition, sustainable water availability, supply chain development, and investment requirements continue to influence the economic competitiveness of green hydrogen in comparison with conventional energy systems.

Considering the rapid advancement of hydrogen technologies and increasing global investment in renewable energy, there is a need for an updated and comprehensive review that integrates technological developments, sustainability benefits, industrial applications, commercialization challenges, and future prospects. Such an assessment will assist policymakers, industrial practitioners, researchers, and investors in understanding the strategic role of green hydrogen in supporting sustainable development and achieving long-term carbon neutrality objectives.

The objectives of this study are to evaluate the current status of green hydrogen production technologies, examine its contribution toward environmental and industrial sustainability, assess major technological and economic challenges, review recent policy initiatives, and identify future research directions for accelerating the transition toward a sustainable hydrogen economy.

2. Literature Review

Hydrogen has long been recognized as a versatile energy carrier with considerable potential to support global decarbonization and renewable energy integration. Early investigations primarily focused on hydrogen production through fossil fuel reforming because of its relatively low production cost and established industrial infrastructure. However, increasing concerns regarding greenhouse gas emissions have shifted research toward renewable hydrogen production technologies, particularly water electrolysis powered by solar and wind energy [3,4].

Numerous studies have investigated different electrolysis technologies including alkaline water electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis cells. Among these technologies, alkaline electrolysis is considered commercially mature and economically attractive, whereas proton exchange membrane systems offer superior operational flexibility and compatibility with intermittent renewable electricity generation. Solid oxide electrolysis demonstrates high electrical efficiency owing to its elevated operating temperature but continues to face challenges associated with material degradation and long-term durability [4,5].

Recent research has further demonstrated that green hydrogen can effectively address one of the major limitations of renewable energy systems by providing long-duration energy storage. Surplus electricity



generated from solar photovoltaic and wind power plants can be converted into hydrogen through electrolysis, stored for extended periods, and subsequently utilized for electricity generation, industrial heating, transportation, or chemical manufacturing. This power-to-hydrogen approach enhances renewable energy utilization while improving overall grid stability and energy security [2,3].

Several investigators have emphasized the role of green hydrogen in decarbonizing difficult-to-abate sectors such as steel manufacturing, cement production, fertilizer industries, petroleum refining, maritime transport, and aviation. Unlike battery-based electrification, hydrogen can supply high-temperature process heat and serve as a chemical feedstock, thereby enabling substantial reductions in industrial carbon emissions [5,6].

From a sustainability perspective, integrated assessment frameworks have become increasingly important for evaluating emerging energy technologies. Jena et al. proposed the Madhab's EEE Impact Model for comparing renewable and conventional energy systems and reported that solar energy exhibited the lowest environmental, efficiency, and economic impact index among the investigated alternatives [7]. Further studies by Jena et al. highlighted the importance of sustainable manufacturing practices, environmental impact assessment, Industry 4.0 technologies, and artificial intelligence in improving industrial sustainability and facilitating renewable energy adoption [8,9]. These findings suggest that future hydrogen systems should not be evaluated solely based on production efficiency but also considering their environmental, economic, technological, and social impacts.

Recent advances in green hydrogen research have increasingly focused on improving the efficiency, economic feasibility, and sustainability of hydrogen production systems. Several studies have demonstrated that declining renewable electricity costs are significantly improving the competitiveness of green hydrogen compared with conventional hydrogen production pathways. As solar photovoltaic and wind energy continue to achieve lower levelized costs of electricity, the production cost of green hydrogen is expected to decrease substantially over the coming decade, thereby accelerating its commercialization across multiple industrial sectors [16,17]. Technological improvements in electrolyzer design, catalyst development, and system integration have further enhanced hydrogen production efficiency while reducing operational costs.

Life cycle assessment has become an important tool for evaluating the environmental sustainability of hydrogen production technologies. Comprehensive environmental analyses indicate that green hydrogen generated using renewable electricity exhibits the lowest greenhouse gas emissions among currently available hydrogen production pathways. Nevertheless, researchers have emphasized that the environmental performance of green hydrogen depends not only on the source of electricity but also on water availability, electrolyzer manufacturing processes, equipment recycling, transportation infrastructure, and supply chain management [18,19]. Consequently, integrated life cycle assessments are increasingly recommended for evaluating the long-term sustainability of hydrogen-based energy systems.

Several investigators have examined the role of green hydrogen in supporting sector coupling within integrated energy systems. Hydrogen provides an effective mechanism for connecting electricity, transportation, industrial manufacturing, and heating sectors through power-to-gas technologies. Surplus renewable electricity can be converted into hydrogen during periods of low electricity demand and subsequently utilized in fuel cells, industrial furnaces, synthetic fuel production, or natural gas blending. Such integrated energy systems significantly improve renewable energy utilization while enhancing overall system flexibility and resilience [20,21].

Hydrogen storage technologies continue to receive considerable research attention because efficient storage remains one of the primary challenges associated with large-scale hydrogen deployment. Researchers have investigated compressed gaseous storage, cryogenic liquid hydrogen, underground geological storage, and solid-



state hydrogen storage using metal hydrides and advanced nanomaterials. Although each technology offers specific advantages, further improvements in storage capacity, safety, material durability, and cost reduction remain necessary before widespread commercialization can be achieved [22,23].

The application of green hydrogen within heavy industries has also been extensively investigated. Steel manufacturing accounts for a significant proportion of global industrial carbon emissions because conventional blast furnace processes rely on coke as the primary reducing agent. Recent investigations demonstrate that hydrogen-based direct reduced iron technologies can substantially reduce carbon dioxide emissions while maintaining production efficiency. Similar opportunities have been identified within cement manufacturing, ammonia production, petroleum refining, glass manufacturing, and chemical processing industries, where hydrogen can replace fossil fuels in high-temperature industrial operations [24,25].

Economic feasibility remains one of the most important factors influencing future hydrogen commercialization. Techno-economic analyses indicate that the cost of renewable electricity, electrolyzer efficiency, capacity utilization, financing conditions, and infrastructure development collectively determine the competitiveness of green hydrogen. Several studies predict that continued technological innovation, mass production of electrolyzers, and economies of scale will reduce hydrogen production costs sufficiently to compete with conventional fossil fuel-derived hydrogen before 2035 in many regions [17,26].

Policy interventions have emerged as another major driver supporting hydrogen development worldwide. Governments have introduced financial incentives, carbon pricing mechanisms, research grants, production subsidies, tax incentives, and infrastructure investment programs to accelerate hydrogen commercialization. International cooperation involving technology transfer, hydrogen certification, common safety standards, and cross-border hydrogen trade is expected to play an increasingly important role in establishing a global hydrogen economy [27,28].

Digital technologies are expected to transform future hydrogen production and management systems. Artificial intelligence, machine learning, digital twins, predictive maintenance, and advanced optimization algorithms can improve electrolyzer performance, forecast renewable electricity generation, optimize hydrogen storage, and reduce operational costs. Integration of Industry 4.0 technologies with renewable hydrogen systems has the potential to significantly enhance production efficiency, operational reliability, and environmental sustainability [29]. These findings are consistent with the sustainable manufacturing studies conducted by Jena et al. [7–9], which demonstrated that intelligent digital technologies improve energy efficiency and environmental performance across industrial applications.

Recent literature has increasingly recognized that the successful deployment of green hydrogen depends not only on technological innovation but also on effective governance, policy frameworks, environmental accountability, and organizational readiness. Ajanovic and Haas [13] argued that the long-term success of the hydrogen economy will depend on achieving cost competitiveness, expanding renewable energy capacity, and establishing reliable hydrogen infrastructure. Similarly, the International Energy Agency emphasized that accelerated investment in clean hydrogen technologies and supportive regulatory frameworks are essential for achieving global net-zero emission targets by 2050 [14]. The United Nations has also highlighted that the transition toward renewable energy technologies such as green hydrogen directly contributes to several Sustainable Development Goals (SDGs), particularly those related to affordable and clean energy, sustainable industrialization, responsible production, and climate action [15]. Beyond technological considerations, recent studies have demonstrated that organizational digital transformation and intelligent automation can significantly enhance operational efficiency and improve the adoption of sustainable technologies within industrial sectors [10]. Furthermore, environmental governance, transparent ESG reporting, and effective monitoring mechanisms



are becoming increasingly important for ensuring that hydrogen projects deliver genuine environmental benefits while minimizing the risks of greenwashing and improving corporate accountability [11]. The successful implementation of national hydrogen strategies also requires strong institutional support, stakeholder collaboration, and public acceptance, as broader governance and policy environments substantially influence the adoption of emerging sustainable energy technologies [12]. Collectively, these studies indicate that green hydrogen development should be supported by integrated technological, institutional, environmental, and governance frameworks to maximize its contribution toward sustainable economic development and long-term carbon neutrality.

Overall, recent literature indicates that green hydrogen has evolved from an emerging research topic into a strategic component of future sustainable energy systems. Continued advancements in renewable electricity generation, electrolyzer technology, hydrogen storage, digitalization, and supportive policy frameworks are expected to accelerate commercialization while contributing significantly to global decarbonization, energy security, and sustainable industrial development [30].

Although the existing literature clearly demonstrates the significant potential of green hydrogen, comprehensive studies integrating production technologies, sustainability assessment, industrial applications, policy initiatives, commercialization barriers, and future prospects remain relatively limited. Therefore, a holistic review is necessary to provide a clearer understanding of the strategic role of green hydrogen in achieving sustainable development.

2.1 Research Gap

The existing body of literature has established green hydrogen as a promising alternative energy carrier capable of supporting global decarbonization and renewable energy integration. Most previous studies have concentrated on specific aspects such as hydrogen production technologies, electrolysis efficiency, storage systems, transportation methods, or fuel cell applications. Although these investigations have significantly advanced scientific understanding, relatively few studies have integrated technological, environmental, economic, industrial, and policy dimensions within a comprehensive sustainability framework [3–6]. Furthermore, the majority of published research has focused on developed economies, while comparatively limited attention has been given to the opportunities and challenges associated with large-scale implementation in developing countries such as India, where increasing energy demand, rapid industrialization, and ambitious carbon reduction commitments create significant opportunities for green hydrogen deployment.

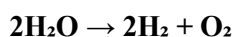
Recent studies have emphasized that future energy systems should be evaluated using multidimensional sustainability assessment approaches that simultaneously consider environmental performance, economic feasibility, technological maturity, energy security, and policy effectiveness. Jena et al. [7–9] demonstrated the importance of integrated sustainability assessment models for evaluating renewable energy technologies and improving industrial environmental performance. However, comprehensive reviews linking green hydrogen with sustainable manufacturing, circular economy principles, digital transformation, and national energy security remain limited. In addition, rapid advancements in electrolyzer technologies, declining renewable electricity costs, artificial intelligence-based energy management, and supportive government policies necessitate an updated assessment of green hydrogen technologies. Therefore, this study attempts to bridge these research gaps by providing a comprehensive review of production technologies, industrial applications, sustainability benefits, commercialization challenges, and future research opportunities associated with green hydrogen.

3. Green Hydrogen Production Technologies



Green hydrogen is produced through the electrolysis of water using electricity generated exclusively from renewable energy resources such as solar, wind, hydropower, or biomass. During electrolysis, electrical energy separates water molecules into hydrogen and oxygen without producing carbon dioxide emissions. Consequently, the environmental performance of green hydrogen is directly influenced by the renewable energy source supplying electricity to the electrolyzer. As renewable electricity becomes increasingly affordable and widely available, green hydrogen production is expected to become more economically competitive in the coming years [2,3].

The electrochemical decomposition of water is represented by the following reaction:



Among commercially available technologies, alkaline water electrolysis remains the most mature and widely deployed process for industrial hydrogen production. This technology utilizes an alkaline electrolyte, generally potassium hydroxide or sodium hydroxide, to facilitate ionic conduction between electrodes. Alkaline electrolyzers are characterized by relatively low capital costs, long operational lifetimes, and reliable performance under continuous operating conditions. However, their comparatively slower dynamic response limits their effectiveness when integrated with highly fluctuating renewable electricity generation [4].

Proton Exchange Membrane (PEM) electrolysis has gained considerable attention because of its compact design, high operational efficiency, rapid start-up capability, and excellent compatibility with intermittent renewable energy sources. PEM systems employ a solid polymer electrolyte membrane that allows selective proton transport while preventing gas crossover, thereby producing high-purity hydrogen. Despite these advantages, the widespread commercialization of PEM electrolyzers is constrained by the high cost of noble metal catalysts and membrane materials required for efficient operation [5].

Solid Oxide Electrolysis Cell (SOEC) technology represents another promising approach for future hydrogen production. Operating at temperatures between 700°C and 900°C, SOEC systems achieve superior electrical efficiency by utilizing thermal energy in addition to electricity during water decomposition. Although laboratory-scale investigations have demonstrated encouraging performance, long-term material degradation, thermal stress, and high manufacturing costs continue to limit commercial deployment [5,6].

The integration of electrolysis systems with renewable electricity generation significantly enhances the utilization of solar and wind energy. During periods of excess electricity generation, renewable energy that would otherwise be curtailed can be converted into hydrogen and stored for future use. This power-to-hydrogen approach improves overall energy system flexibility, facilitates seasonal energy storage, and strengthens grid reliability while supporting large-scale renewable energy integration [2].

4. Applications of Green Hydrogen

Green hydrogen possesses exceptional versatility because it can function both as a clean fuel and as an industrial feedstock. One of its most significant applications is in the transportation sector, particularly for heavy-duty vehicles, buses, railway locomotives, maritime vessels, and aviation. Fuel cell electric vehicles powered by hydrogen offer longer driving ranges and shorter refueling times compared with conventional battery electric vehicles, making them suitable for commercial transportation requiring continuous operation [4,6].

In the industrial sector, green hydrogen is increasingly recognized as an effective solution for decarbonizing energy-intensive manufacturing processes. Steel manufacturing traditionally relies on coke as a reducing agent



during iron ore reduction, generating substantial carbon dioxide emissions. Replacing coke with green hydrogen enables direct reduction of iron ore while producing water vapor instead of carbon dioxide, thereby significantly reducing industrial emissions. Similar opportunities exist within cement manufacturing, petroleum refining, chemical processing, and fertilizer industries where hydrogen serves either as a reducing agent or as an essential feedstock [5].

Hydrogen also plays an important role in electricity generation and renewable energy storage. Surplus electricity produced by solar photovoltaic and wind power plants can be converted into hydrogen through electrolysis and subsequently reconverted into electricity using fuel cells or hydrogen turbines during periods of peak demand. This capability enables long-duration and seasonal energy storage, thereby improving renewable energy utilization and enhancing power system stability [2,3].

In addition to industrial and energy applications, green hydrogen contributes to the production of synthetic fuels, ammonia, methanol, and various chemical products. Green ammonia has emerged as an important carbon-free fuel for maritime transportation and as a sustainable raw material for fertilizer production. Consequently, hydrogen is expected to become a central component of future integrated renewable energy and industrial systems.

5. Sustainability Benefits of Green Hydrogen

Green hydrogen contributes significantly to sustainable development by simultaneously addressing environmental, economic, and social challenges associated with conventional fossil fuel consumption. From an environmental perspective, green hydrogen eliminates direct carbon dioxide emissions during production and utilization because water electrolysis powered by renewable electricity does not involve fossil fuel combustion. Furthermore, hydrogen fuel cells generate electricity through electrochemical reactions, producing only water as the reaction product. Consequently, the adoption of green hydrogen substantially reduces greenhouse gas emissions, particulate matter, sulfur oxides, and nitrogen oxides, thereby improving air quality and supporting global climate change mitigation efforts [1,5].

Economic sustainability is another important advantage associated with green hydrogen. Increasing domestic hydrogen production reduces dependence on imported fossil fuels, enhances national energy security, and stabilizes long-term energy supply. The rapid expansion of hydrogen industries is also expected to generate substantial employment opportunities across renewable energy generation, electrolyzer manufacturing, hydrogen infrastructure development, transportation, equipment maintenance, and research activities. Declining renewable electricity costs and continuous technological innovation are expected to improve the economic competitiveness of green hydrogen during the coming decade [2,6].

From a social perspective, green hydrogen supports sustainable industrial development, cleaner urban environments, and improved public health through reduced air pollution. The technology also contributes directly to several Sustainable Development Goals, including affordable and clean energy (SDG 7), industry, innovation and infrastructure (SDG 9), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12), and climate action (SDG 13). Recent sustainability assessment frameworks developed by Jena et al. [7–9] further emphasize that integrated environmental, economic, and technological evaluations are essential for supporting sustainable renewable energy transitions and evidence-based policymaking.



6. Challenges Associated with Green Hydrogen

Despite its considerable advantages, green hydrogen continues to face several technological and economic challenges that limit large-scale commercialization. One of the most significant barriers is the high cost of hydrogen production, primarily due to the substantial electricity consumption required during water electrolysis. Renewable electricity currently represents the largest component of production cost, although continued reductions in solar and wind energy prices are expected to improve future competitiveness [2].

The capital investment associated with electrolyzer manufacturing also remains relatively high. Advanced PEM electrolyzers require expensive catalysts such as platinum and iridium, while SOEC technologies require specialized ceramic materials capable of operating under extremely high temperatures. Continued research is therefore focused on developing low-cost catalyst materials, improving electrolyzer durability, and increasing manufacturing efficiency [5].

Hydrogen storage and transportation present additional engineering challenges because hydrogen possesses very low volumetric energy density under ambient conditions. Efficient storage requires high-pressure compression, cryogenic liquefaction, or conversion into hydrogen carriers such as ammonia or methanol, each of which increases overall system complexity and cost. Furthermore, the development of dedicated pipelines, storage terminals, refueling stations, and international hydrogen supply chains requires substantial long-term investment [4,6].

Policy uncertainty, regulatory frameworks, safety standards, and financing mechanisms also influence hydrogen commercialization. Stable government policies, financial incentives, carbon pricing mechanisms, and international collaboration will therefore remain essential for accelerating industrial investment and widespread hydrogen adoption.

7. Future Prospects

The future of green hydrogen appears highly promising owing to continuous technological innovation, declining renewable electricity costs, and increasing global investment in sustainable energy infrastructure. Several countries have announced ambitious hydrogen roadmaps supporting large-scale electrolyzer manufacturing, renewable energy expansion, hydrogen transportation networks, and international hydrogen trade. These initiatives are expected to significantly reduce production costs while improving global hydrogen supply chains [1,6].

Digital technologies including artificial intelligence, machine learning, Industry 4.0, digital twins, and predictive maintenance systems are expected to further enhance hydrogen production efficiency by optimizing electrolyzer operation, improving renewable energy forecasting, reducing maintenance costs, and maximizing system reliability. Recent investigations by Jena et al. [8,9] have demonstrated that intelligent manufacturing systems significantly improve energy efficiency and environmental performance, indicating similar opportunities for future hydrogen production facilities.

India possesses substantial potential to become one of the world's leading producers of green hydrogen due to abundant solar radiation, favorable wind resources, expanding renewable electricity capacity, and supportive government policies. Successful implementation of the National Green Hydrogen Mission will strengthen energy independence, promote sustainable industrialization, attract foreign investment, and contribute significantly toward achieving India's net-zero emission target by 2070 [6].



8. Conclusion

Green hydrogen has emerged as one of the most promising alternative energy sources capable of supporting the global transition toward sustainable development and carbon neutrality. Produced using renewable electricity through water electrolysis, it provides a clean, versatile, and efficient energy carrier suitable for transportation, power generation, industrial manufacturing, and long-duration energy storage. Compared with conventional fossil fuel-based hydrogen production, green hydrogen offers substantial environmental benefits through significant reductions in greenhouse gas emissions and air pollutants.

Although challenges related to production costs, infrastructure development, hydrogen storage, and policy implementation remain, continuous technological innovation, declining renewable energy costs, and increasing international investment are expected to accelerate commercialization over the coming years. Integrating green hydrogen with renewable energy systems, artificial intelligence, and sustainable manufacturing practices will further enhance its contribution toward global energy security and environmental sustainability. Therefore, green hydrogen is expected to become a fundamental component of future low-carbon energy systems and play a decisive role in achieving sustainable economic growth and international climate commitments.

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