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Review Article

Green Hydrogen for a Sustainable Energy Future: Production Technologies, Challenges, Opportunities, and the Pathway to the 2030 Agenda

Anil Kaushik[1], Arun Kumar[2,*]

[1]Assistant Professor, Department of Physics Government College for Women, Gohana (Sonepat) 131301, Haryana, India
[2]Assistant Professor, Department of Physics Government College Bahadurgarh, (Jhajjar) 124507, Haryana, India
*Corresponding author, E-mail: arun250981@gmail.com

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ABSTRACT
Green hydrogen is increasingly recognized as a strategic energy carrier for decarbonizing energy-intensive sectors and supporting the transition toward sustainable and resilient energy systems. This review comprehensively examines the technological pathways, challenges, opportunities, and policy dimensions associated with green hydrogen production within the framework of the United Nations 2030 Agenda for Sustainable Development. Key production routes, including water electrolysis, photovoltaic- and wind-powered electrolysis, ethanol steam reforming, biomass gasification, and high-temperature thermochemical cycles, are critically discussed with respect to their operating principles, technological maturity, efficiency, environmental performance, and scalability. Particular attention is given to hydrogen purification and quality standards, storage and transportation, and the potential repurposing of natural gas infrastructure for hydrogen distribution. The review also examines Power-to-Gas systems, carbon capture and utilization, circular-economy approaches, and Industry 4.0 technologies as enabling strategies for improving system integration, resource efficiency, and energy-system flexibility. Furthermore, the roles of government incentives, regulatory frameworks, research and development, and public–private partnerships in accelerating hydrogen deployment are evaluated. The contribution of green hydrogen to key Sustainable Development Goals, particularly SDGs 7, 9, 12, 13, 15, and 17, is highlighted. Despite significant technological progress, challenges related to production costs, energy efficiency, infrastructure, critical-material supply chains, storage, transportation, and regulatory harmonization remain. Overall, the review demonstrates that coordinated technological innovation, strategic investment, international collaboration, and supportive policies are essential for realizing the potential of green hydrogen as a cornerstone of a low-carbon, resilient, interconnected, and sustainable global energy system.

1. Introduction

Green hydrogen is increasingly regarded as a key component of the global transition toward low-carbon energy systems, with significant potential to address climate change, energy security, and sustainable-development challenges. Its production using renewable energy offers an opportunity to reduce greenhouse-gas emissions while facilitating the integration of variable renewable resources into future energy systems. In this context, green hydrogen can support the decarbonization of sectors that are difficult to electrify directly and promote technological innovation across energy, industrial, and transportation applications. Its development is also closely connected with the objectives of the 2030 Agenda for Sustainable Development and relevant Sustainable Development Goals (SDGs), particularly those concerning clean energy, sustainable infrastructure, innovation, and climate action. This paper critically reviews the principal technologies, production methodologies, and structural complexities of green hydrogen production, with particular emphasis on its contribution to global decarbonization pathways and sustainable development.

The adoption of green hydrogen can provide significant environmental and socio-economic advantages by enabling renewable energy to be stored and utilized more flexibly. Its production from renewable electricity can help manage the variability of solar and wind resources while improving the reliability and resilience of energy systems. Beyond electricity generation, hydrogen can serve as a versatile energy carrier across transportation, industrial processes, and heating applications, thereby creating opportunities for substantial reductions in carbon emissions. It is particularly relevant for hard-to-decarbonize sectors such as steelmaking, chemical production, and long-distance transport, where direct electrification may be technically challenging. In aviation, emerging hydrogen-based technologies, including fuel cells and hydrogen combustion systems, are being investigated as potential pathways toward lower-carbon and, ultimately, carbon-neutral air transport, thereby addressing the sector's persistent decarbonization challenges [1].

Within the framework of COP28, 198 countries endorsed the Dubai Agreement, reaffirming the urgent requirement for rapid and sustainable reductions in greenhouse-gas emissions consistent with efforts to limit global warming to 1.5 °C. The agreement identifies several important pathways for accelerating the global energy transition, including:

- Accelerating the progressive reduction of coal consumption in energy systems.
- Transforming global energy systems toward net-zero emissions by mid-century through the increased deployment of low- and zero-carbon energy sources and fuels.
- Promoting an equitable and orderly transition away from fossil fuels in energy systems while strengthening near-term actions during the present decade to support the achievement of net-zero emissions by 2050.
- Accelerating the development and deployment of low- and zero-emission technologies, including renewable energy, nuclear energy, and carbon capture and storage, particularly for sectors where emissions are difficult to eliminate.
- Achieving substantial reductions in global non-CO_2 greenhouse-gas emissions, with particular emphasis on reducing methane emissions by 2030.

Green hydrogen represents a promising pathway for supporting the objectives established under the Dubai Agreement and facilitating the transition toward a sustainable, low-emission energy system. Hydrogen possesses a high specific energy and can function as an efficient energy carrier; when utilized in combustion processes or electrochemical fuel cells, it releases energy with water as the primary reaction product, offering an important environmental advantage over carbon-based fuels. Although hydrogen exhibits limited solubility in water and many other liquids, its physical behavior under elevated pressure can facilitate more effective storage and handling strategies. When generated using renewable energy, green hydrogen can provide a low-carbon fuel and chemical feedstock with applications across diverse sectors. These include transportation, industrial manufacturing, energy storage, and other energy-intensive processes, making green hydrogen an important component of broader decarbonization strategies [2]. Its major applications across different sectors are illustrated in Fig. 1.

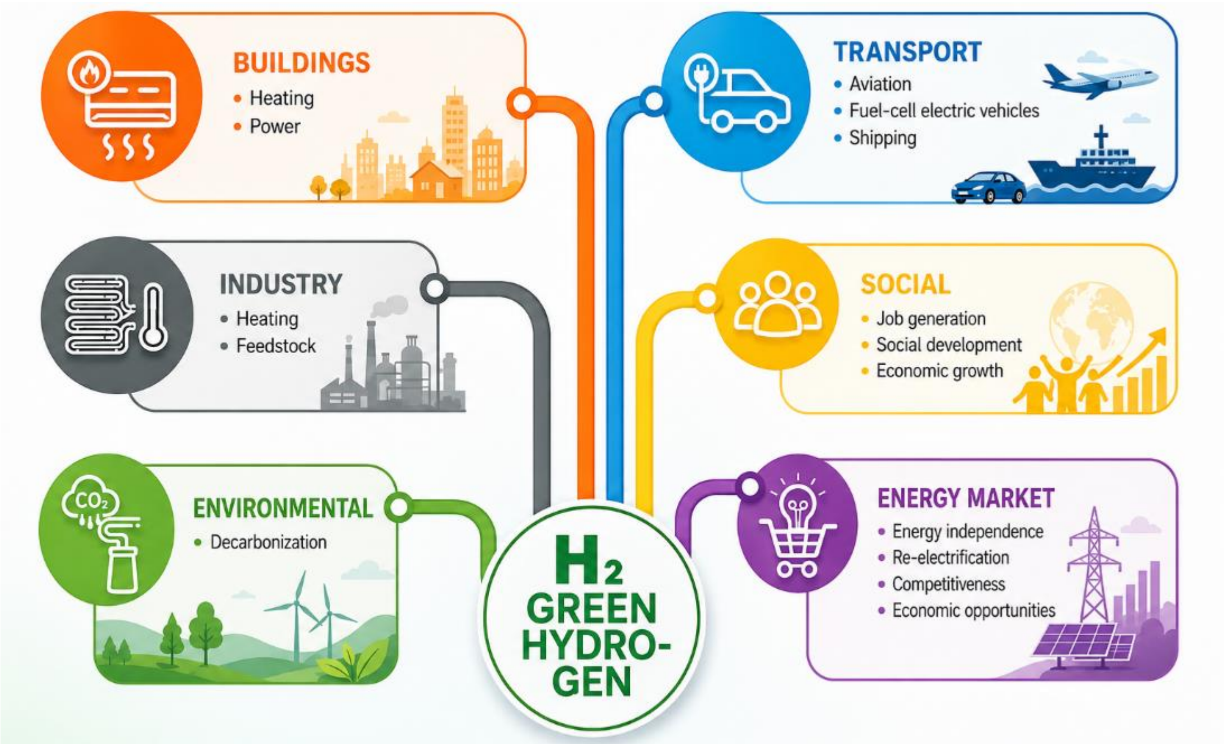

Figure 1: Overview of the significance of green hydrogen production and its diverse applications in supporting the transition toward a sustainable and low-carbon energy system.

Within the ongoing global transition toward sustainable and low-carbon energy systems, green hydrogen is increasingly recognized as an important energy carrier for transportation, power, industrial, and heating applications. Its adaptability across multiple sectors, together with its potential to substantially reduce greenhouse-gas emissions, makes hydrogen an important component of future energy systems. In particular, its use in industrial applications is gaining considerable attention because of its distinctive physicochemical characteristics and the growing demand for cleaner alternatives to fossil-based fuels and feedstocks [3].

In the transportation sector, hydrogen can be employed in fuel cell electric vehicles (FCEVs), including passenger cars, heavy-duty trucks, and buses. In these vehicles, hydrogen is electrochemically converted into electricity within a fuel cell, with water and heat as the principal reaction products, thereby avoiding direct tailpipe carbon emissions. Hydrogen-powered passenger vehicles have already been introduced commercially, while demonstration and pilot programs for hydrogen-fueled trucks and buses are being developed in several regions. The application of hydrogen in transportation could therefore contribute to reducing the sector's dependence on fossil fuels and lowering its greenhouse-gas emissions, particularly in heavy-duty and long-distance mobility applications.

Hydrogen can also function as an effective medium for storing energy generated from renewable sources. Through water electrolysis, excess electricity produced by solar and wind installations can be converted into chemical energy in the form of hydrogen. The stored hydrogen can subsequently be utilized to produce electricity during periods of elevated demand or when renewable generation is insufficient. This capability provides a means of balancing fluctuations in renewable power generation, supporting grid stability, and improving the utilization of intermittent renewable resources. Consequently, hydrogen-based energy storage can reduce dependence on fossil-fuel-based backup generation and contribute to a more flexible, resilient, and reliable low-carbon energy system [4].

In the chemical industry, hydrogen serves as an essential feedstock for several large-scale processes, particularly ammonia synthesis for fertilizer production and hydroprocessing operations in petroleum refining. It is also involved in hydrogenation reactions used in the manufacture of various chemicals, materials, and pharmaceutical products. Replacing conventionally produced hydrogen with renewable-based green hydrogen in these applications can substantially lower the associated carbon footprint by reducing dependence on fossil-derived hydrogen. Such a transition could therefore contribute significantly to cleaner and more sustainable industrial production [5].

The steel industry represents another major opportunity for hydrogen-based decarbonization. Conventional iron and steelmaking relies heavily on coal and coke as reducing agents, resulting in substantial carbon dioxide emissions. Renewable hydrogen can serve as an alternative reducing agent in direct-reduction processes, producing water rather than carbon dioxide as the principal by-product of the reduction reaction. The large-scale integration of hydrogen-based steelmaking could consequently reduce the carbon intensity of steel production and support the industry's transition toward low-emission manufacturing [6].

In the heating sector, hydrogen has potential applications in residential, commercial, and industrial heating systems, including boilers and other hydrogen-compatible heating technologies. Its relevance is particularly evident in regions where natural gas remains an important source of thermal energy, as hydrogen may be incorporated into existing gas infrastructure subject to appropriate technical modifications, safety considerations, and compatibility requirements. The substitution or partial integration of hydrogen can reduce reliance on conventional fossil fuels and, when the hydrogen is produced from renewable sources, contribute to lowering greenhouse-gas emissions associated with heat generation [7].

Forecasting future hydrogen demand remains subject to considerable uncertainty because of differences in technological development, policy support, energy-market conditions, and the pace of decarbonization across sectors. Nevertheless, available projections consistently indicate that hydrogen is likely to become an increasingly important component of future energy systems. Several scenarios estimate global hydrogen demand at approximately 110 million tonnes (Mt) by 2030, with a substantial share expected to originate from clean or low-carbon production pathways [8-11]. Although estimates differ among individual studies and scenarios, the overall trend points toward strong growth in hydrogen consumption, with global demand potentially increasing to nearly twice its present level by 2050 as its applications expand across industrial, transport, energy-storage, and other hard-to-abate sectors.

The application of hydrogen in aviation is an emerging technological pathway with considerable potential to reduce the sector's carbon intensity and support the development of more sustainable air transportation. Hydrogen can primarily be utilized in aviation through two approaches: direct combustion in modified engines or conversion into electricity using hydrogen fuel cells to drive electric propulsion systems. In the combustion pathway, hydrogen can be burned in appropriately modified internal-combustion engines or gas turbines, although its distinct combustion characteristics require substantial modifications to conventional propulsion technologies. Airbus has proposed its ZEROe aircraft concept as a potential hydrogen-powered commercial aircraft, including configurations based on turbofan engines adapted for hydrogen combustion, with entry into service targeted for the mid-2030s [1].

An alternative approach involves hydrogen fuel cells, which electrochemically convert hydrogen into electricity that can subsequently operate electric motors and propellers. This technology is being investigated for regional and short-distance aircraft applications, where its technical characteristics may be particularly advantageous. Companies such as ZeroAvia and Universal Hydrogen have been developing hydrogen-electric aviation technologies, including aircraft demonstrations and systems designed to integrate hydrogen fuel-cell powertrains into existing regional aircraft. These developments illustrate the growing technological interest in hydrogen as a potential pathway for reducing aviation-related emissions, although substantial challenges involving aircraft weight, hydrogen storage, infrastructure, safety, and system scalability must still be addressed before widespread commercial deployment [2].

Hydrogen-based propulsion technologies offer several potential advantages for reducing the environmental impact of aviation. From an operational perspective, hydrogen combustion does not generate carbon dioxide from the fuel itself, while hydrogen fuel cells produce electricity through an electrochemical reaction, with water as the principal reaction product. Hydrogen fuel-cell systems may also provide higher energy-conversion efficiency than conventional combustion-based propulsion under suitable operating conditions, potentially reducing the amount of energy required to deliver a given propulsion output. Furthermore, the use of electric motors in hydrogen fuel-cell aircraft can substantially reduce propulsion-related noise compared with conventional gas-turbine engines. These characteristics make hydrogen an attractive option for developing quieter and lower-carbon aviation technologies, particularly for short- and medium-range aircraft [3].

Despite its potential advantages, the integration of hydrogen into aviation presents several important technical, economic, and safety-related challenges. Hydrogen has a considerably lower volumetric energy density than conventional aviation fuels, meaning that substantially larger storage volumes are required to carry an equivalent amount of usable energy. This limitation may necessitate the development of specialized storage systems, including lightweight high-pressure tanks or cryogenic systems capable of maintaining hydrogen in liquid form, thereby creating additional challenges related to aircraft design, weight, thermal management, and available storage space [4].

The large-scale adoption of hydrogen-powered aircraft would also require major investments in supporting infrastructure. Airports would need dedicated systems for hydrogen production or delivery, liquefaction or compression, storage, distribution, and aircraft refueling. Establishing such infrastructure across airports would involve significant capital expenditure and the development of appropriate technical standards and supply chains. In addition, hydrogen's high flammability necessitates rigorous safety protocols throughout production, transportation, storage, and aircraft refueling operations. Consequently, reliable containment systems, leak detection, ventilation, emergency-response procedures, and stringent operational standards will be essential for the safe deployment of hydrogen in aviation [4].

Despite the technical and infrastructural barriers associated with hydrogen aviation, its long-term prospects remain promising. Continued progress in renewable-energy deployment and green hydrogen production, together with advances in hydrogen fuel-cell and combustion technologies, could strengthen the feasibility of hydrogen-powered aircraft and contribute to the long-term decarbonization of air transport. Ongoing research and development by governments, aerospace organizations, and technology companies is focused on improving propulsion efficiency, hydrogen storage, aircraft integration, and operational safety, while pilot and demonstration projects are being undertaken to assess the practical performance and scalability of these technologies. Although substantial technological and economic uncertainties remain, continued innovation in hydrogen combustion engines and fuel-cell-based propulsion could establish hydrogen as an important option for reducing aviation emissions. In this context, the development of hydrogen aviation may contribute to broader climate objectives and support the sustainable-development ambitions of the 2030 Agenda [5].

The growing importance of hydrogen in contemporary energy systems is associated with its distinctive physicochemical properties, broad range of applications, and potential contribution to the development of sustainable energy pathways. As the most abundant element in the universe, hydrogen can serve as an energy carrier and industrial feedstock capable of supporting emissions reduction across multiple sectors, including transportation, industrial manufacturing, and electricity generation. Its production from diverse domestic energy resources can also enhance energy security by reducing dependence on imported fossil fuels and strengthening the resilience of national energy systems. Furthermore, hydrogen can be utilized in fuel-cell vehicles, industrial processes, and energy-storage applications, providing flexibility across different components of the energy system. Electrolytic hydrogen production can additionally convert surplus electricity from renewable sources into a storable energy form, thereby improving the utilization of variable resources such as wind and solar power. This capability can help balance fluctuations between electricity supply and demand, reduce renewable-energy curtailment, and support greater stability and flexibility of future power grids [12].

The increasing global demand for hydrogen is creating substantial opportunities for technological innovation, industrial expansion, and employment generation across the hydrogen value chain. Growth in hydrogen production, storage, transportation, distribution, and end-use applications can stimulate the development of new industries and skilled employment opportunities. In particular, the transition toward green hydrogen can assist countries in achieving greenhouse-gas emission-reduction objectives while supporting the development of more sustainable and resilient economies.

Significant technological progress is being pursued to improve hydrogen production, storage, and transportation. Advances in high-efficiency electrolysis and emerging methane-pyrolysis technologies aim to improve production performance and reduce environmental impacts, while innovative storage approaches, including metal hydrides and liquid-hydrogen systems, are being investigated to overcome limitations associated with conventional storage methods. The expansion of hydrogen infrastructure, encompassing production facilities, distribution systems, pipelines, storage installations, and refueling stations, can generate opportunities for infrastructure investment and specialized employment. Regions with substantial solar and wind resources may particularly benefit from renewable hydrogen production, potentially promoting regional economic development while reducing dependence on imported energy. Furthermore, integrating hydrogen production into circular-economy frameworks can improve overall resource efficiency by utilizing suitable industrial waste streams and recovering the oxygen generated during electrolysis for industrial, chemical, and medical applications [13].

Despite its considerable potential as a low-carbon energy carrier, the large-scale deployment of green hydrogen continues to face significant technical, economic, infrastructural, and institutional barriers. The relatively high cost of hydrogen production, together with expenses associated with compression, storage, transportation, and distribution, can limit its competitiveness with established fossil-based energy pathways. These challenges are further compounded by insufficient hydrogen infrastructure, limited supply-chain capacity, and the absence of harmonized regulatory and safety frameworks in many regions. Addressing these barriers requires continued improvements in electrolyzer efficiency, durability, and scalability, alongside the development of advanced and cost-effective storage technologies, including metal-hydride systems and cryogenic storage. In parallel, clear policy frameworks, financial incentives, technical standards, and long-term investment strategies are necessary to reduce market uncertainty and accelerate the deployment of hydrogen technologies. Collectively, these measures can strengthen the economic viability of green hydrogen and facilitate its integration into future low-carbon energy systems.

Consistent with the commitments established through the Dubai Agreement at COP28, this study considers green hydrogen an important technological pathway for advancing global decarbonization efforts. The agreement emphasizes the need to progressively reduce dependence on coal, increase the deployment of low- and zero-carbon energy sources, and accelerate the development of technologies capable of supporting substantial emissions reductions. Green hydrogen is closely aligned with these objectives because its production using renewable electricity can provide a low-carbon energy carrier and industrial feedstock for applications across multiple sectors. Its deployment can therefore contribute to reducing fossil-fuel dependence in areas such as industry, transportation, energy storage, and other difficult-to-decarbonize applications, thereby supporting broader efforts to achieve long-term climate and energy-transition targets [14].

The specific contributions of this review can be summarized as follows:

- Comprehensive technological assessment: The review critically evaluates the current state of green hydrogen production technologies, with particular attention to renewable-powered water electrolysis, methane pyrolysis, and other emerging production pathways. It considers their technological characteristics, potential advantages, limitations, and prospects for large-scale deployment.

- Identification of emerging opportunities: The study examines prospective applications of hydrogen beyond conventional energy uses, emphasizing its potential contribution to circular-economy models, regional economic development, energy accessibility, and more decentralized energy systems.
- System-level evaluation: Particular attention is given to the technological and infrastructural complexities associated with hydrogen storage, transportation, and distribution. The review considers issues of scalability, system integration, infrastructure development, and the requirements for establishing interconnected hydrogen networks at national and international scales.
- Socio-economic assessment: The review considers the wider consequences of transitioning toward a hydrogen-based economy, including employment generation, industrial restructuring, technological innovation, regional development, energy security, and potential changes in the geopolitical relationships associated with energy production and trade.
- Strategic alignment with global sustainability frameworks: Finally, the study places green hydrogen within broader international policy and sustainability frameworks, including the 2030 Agenda and COP28 commitments. It evaluates how hydrogen deployment can contribute to long-term decarbonization, sustainable energy development, and the achievement of global climate and sustainability objectives.

This review provides an integrated assessment of the transformative potential of green hydrogen while critically examining the technological, economic, infrastructural, and policy-related barriers that may constrain its large-scale deployment. In addition to identifying these limitations, it discusses potential pathways for improving technological performance, strengthening infrastructure, reducing costs, and establishing supportive policy mechanisms that can facilitate wider adoption. By bringing together these interconnected dimensions, the review seeks to generate practical and scientifically grounded insights for accelerating the development of hydrogen-based energy systems. The study is intended to serve as a useful reference for researchers, policymakers, industrial stakeholders, and other decision-makers involved in advancing green hydrogen technologies and establishing hydrogen as an important component of a sustainable, resilient, and low-carbon energy future.

2. Green Hydrogen Production: Technology Overview

Green hydrogen production involves a range of technological pathways in which renewable energy is utilized to generate hydrogen with reduced environmental impacts. Among these approaches, water electrolysis is one of the most prominent and extensively investigated methods for renewable hydrogen production. This section examines major electrolysis technologies, including alkaline water electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis, with emphasis on their operating principles, technological characteristics, and development status. Particular attention is given to advances in electrocatalysts, membrane materials, electrode configurations, and overall system architecture that seek to improve energy efficiency, durability, scalability, and economic performance [6]. In addition, the coupling of electrolyzers with renewable electricity generated from sources such as solar photovoltaic and wind power is examined, including the challenges associated with variable renewable generation and system integration (Figure 2).

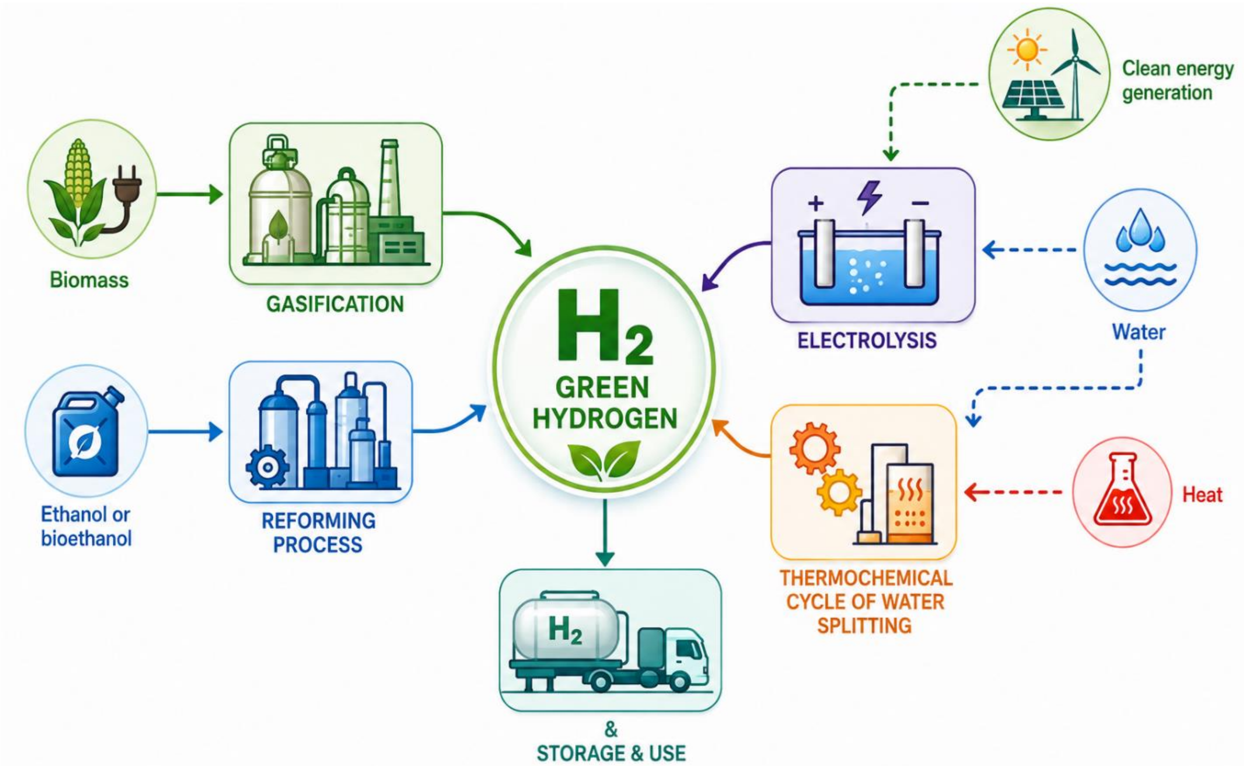

Figure 2: Schematic overview of the principal technological pathways for producing green hydrogen from renewable energy and sustainable feedstocks.

Biomass-based conversion represents another promising pathway for hydrogen production, particularly when sustainably sourced biomass is employed as the feedstock. Thermochemical processes such as steam gasification and pyrolysis can convert biomass into hydrogen-rich gases or intermediate products that can subsequently be processed to obtain hydrogen. When the biomass originates from renewable and responsibly managed resources, these pathways may offer opportunities for reducing net greenhouse-gas emissions and utilizing agricultural, forestry, or other organic residues within a more circular energy system. The overall environmental performance, however, depends on feedstock sustainability, process efficiency, energy requirements, and the management of associated emissions [9].

High-temperature thermochemical routes constitute another technologically advanced category of hydrogen-production processes. These methods employ elevated temperatures to drive chemical reactions that separate water into hydrogen and oxygen, potentially using heat supplied by renewable or other low-carbon energy sources. Among the most extensively investigated approaches are thermochemical water-splitting cycles, including the sulfur–iodine (S–I) cycle. Operating at high temperatures can improve reaction kinetics and potentially increase overall conversion efficiency, but it also introduces significant challenges related to heat management, material durability, corrosion resistance, process complexity, and system integration. Continued research into high-temperature materials, efficient heat recovery, and optimized reaction cycles is therefore essential for determining the practical potential of these technologies for large-scale green hydrogen production [10].

2.1 Electrolytic Hydrogen Generation

Green hydrogen can be produced by splitting water through electrolysis using electricity generated from renewable sources, particularly solar photovoltaic and wind power. This approach provides a promising route for hydrogen generation with low direct greenhouse-gas emissions and enables renewable electricity to be converted into a storable chemical energy carrier [12]. The process begins with the preparation and supply of suitably purified water, generally deionized or demineralized to minimize impurities that could adversely affect electrolyzer performance and component durability. The treated water is subsequently supplied to the electrolyzer, where electrical energy drives the electrochemical reactions responsible for separating water into hydrogen and oxygen (Figure 3).

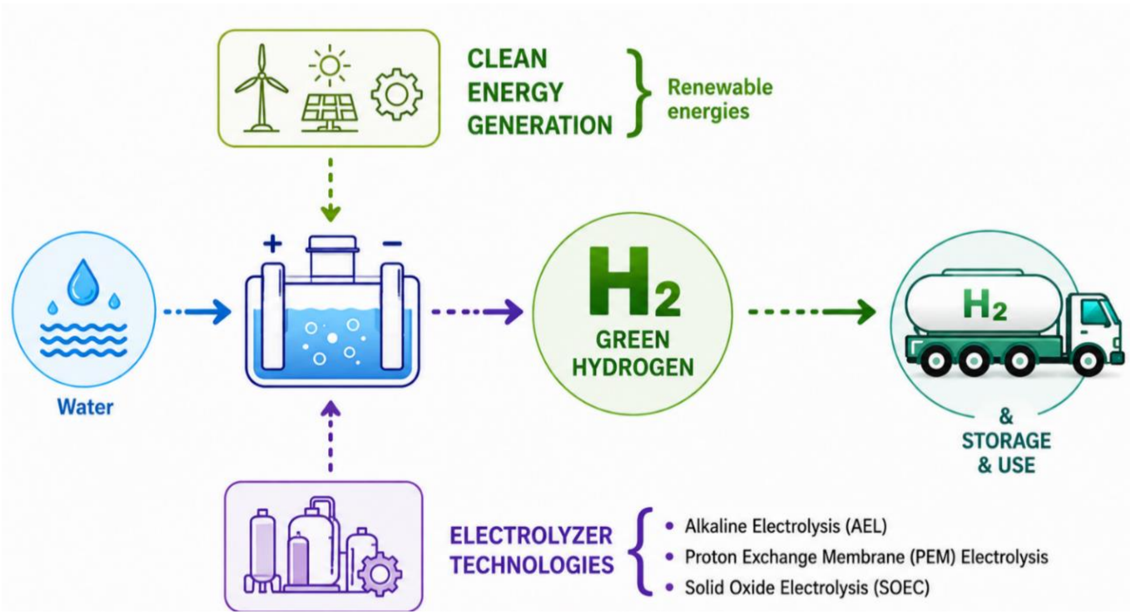

Figure 3: Schematic representation of green hydrogen generation by water electrolysis, illustrating the conversion of renewable electricity and water into hydrogen and oxygen.

A water electrolyzer is an electrochemical device designed to separate water into hydrogen and oxygen by supplying electrical energy to an appropriate electrolysis cell. In a typical configuration, the cell contains two electrodes, an anode and a cathode, which are separated by an ion-conducting membrane or electrolyte [13]. When an external electrical potential is applied, electrochemical reactions occur simultaneously at the two electrodes, resulting in the formation of oxygen at the anode and hydrogen at the cathode.

At the anode, water undergoes an oxidation reaction, releasing oxygen, protons, and electrons:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad (1)$$

The generated protons migrate through the proton-conducting membrane toward the cathode, while the electrons travel through the external electrical circuit. At the cathode, the protons accept electrons and undergo a reduction reaction to form molecular hydrogen:

$$4H^+ + 4e^- \rightarrow 2H_2 \quad (2)$$

Thus, the overall electrolysis process converts water and electrical energy into hydrogen and oxygen. The hydrogen produced at the cathode can subsequently be purified, compressed, stored, or transported for downstream applications, whereas the oxygen generated at the anode may be recovered as a potentially useful by-product.

Water electrolysis encompasses several technological configurations, each characterized by different electrolytes, electrode materials, operating temperatures, and ion-transport mechanisms. Among the principal technologies receiving substantial scientific and industrial attention are alkaline water electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis. Although all three technologies can be coupled with renewable electricity, they differ considerably in terms of efficiency, operating conditions, material requirements, dynamic response, durability, and scalability. The following sections therefore examine the operating principles, major advantages, and principal technical challenges associated with these electrolysis technologies.

2.1.1 Alkaline Water-Splitting Technology (AEL)

Alkaline water electrolysis is one of the most mature hydrogen-production technologies and has been employed commercially for several decades because of its established operating principles, technological reliability, and comparatively extensive industrial experience [14]. In this configuration, an aqueous alkaline solution, commonly potassium hydroxide (KOH) or sodium hydroxide (NaOH), functions as the electrolyte and facilitates the transport of hydroxide ions between the electrodes. Nickel-based or other non-precious-metal electrodes are frequently employed because of their suitable catalytic activity, electrical conductivity, and relatively favorable cost. During operation, water is reduced at the cathode to form hydrogen and hydroxide ions, while hydroxide ions are oxidized at the anode, producing oxygen and water.

The cathodic half-reaction can be represented as:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (3)$$

At the anode, the corresponding oxidation reaction is:

$$2OH^- \rightarrow \tfrac{1}{2}O_2 + H_2O + 2e^- \quad (4)$$

The hydroxide ions generated at the cathode migrate through the alkaline electrolyte toward the anode, thereby sustaining the electrochemical cycle. Hydrogen is consequently collected at the cathode, whereas oxygen is released at the anode. The separation of the product gases is essential for maintaining hydrogen purity and ensuring safe operation.

A major advantage of alkaline electrolysis is its technological maturity and demonstrated capacity for scale-up. The use of relatively abundant electrode materials and well-established system components can contribute to lower capital requirements compared with some alternative electrolyzer technologies [15]. In addition, the long operational experience accumulated with alkaline electrolyzers provides a substantial knowledge base for system design, maintenance, and industrial deployment. These characteristics have enabled alkaline electrolysis to remain an important option for large-scale hydrogen production and its integration with renewable-energy systems [16].

2.1.2 Proton-Exchange Membrane Electrolyzer Technology (PEM)

Proton exchange membrane (PEM) electrolysis is an advanced water-electrolysis technology that employs a solid polymer electrolyte membrane to facilitate proton transport between the anode and cathode. The membrane is commonly based on perfluorosulfonic acid polymers, which provide proton conductivity while helping maintain separation between the hydrogen and oxygen streams. PEM electrolyzers generally utilize highly active precious-metal catalysts, particularly platinum at the cathode and iridium-based materials at the anode, to promote the electrochemical reactions. The principal half-cell reactions can be expressed as:

$$\text{Anode: } H_2O \rightarrow \tfrac{1}{2}O_2 + 2H^+ + 2e^- \quad (5)$$

$$\text{Cathode: } 2H^+ + 2e^- \rightarrow H_2 \quad (6)$$

During operation, water is oxidized at the anode to produce oxygen, protons, and electrons. The protons migrate through the polymer membrane toward the cathode, while the electrons pass through the external electrical circuit. At the cathode, protons combine with electrons to form hydrogen gas.

PEM electrolysis generally operates at relatively low temperatures and is characterized by high current densities, compact system configurations, rapid start-up, and fast dynamic responses. These properties make PEM electrolyzers particularly suitable for coupling with intermittent renewable-energy sources, where the electrical input can fluctuate substantially because of changes in solar irradiance or wind availability [17]. Their ability to respond rapidly to variations in renewable electricity also makes them attractive for decentralized hydrogen production and grid-balancing applications. Nevertheless, the dependence on costly and relatively scarce catalyst materials remains an important challenge. Continued research is therefore focused on improving catalyst utilization, membrane durability, system efficiency, and long-term operational stability while reducing dependence on precious metals. These developments could enhance the economic competitiveness and facilitate the wider deployment of PEM electrolysis in renewable hydrogen systems.

2.1.3 Solid-Oxide Electrolyzer Technology (SOEC)

Solid oxide electrolysis is a high-temperature water-electrolysis technology in which a dense ceramic electrolyte conducts oxide ions between the electrodes. The electrolyte is commonly based on stabilized zirconia materials, such as yttria-stabilized zirconia (YSZ), which can maintain ionic conductivity under elevated operating temperatures [18]. Unlike low-temperature electrolyzers, solid oxide electrolysis can utilize both electrical energy and high-temperature heat, thereby reducing the electrical energy requirement for water splitting under appropriate operating conditions.

At the cathode, steam is reduced to form hydrogen and oxide ions:

$$\text{Cathode: } H_2O + 2e^- \rightarrow H_2 + O^{2-} \quad (7)$$

The oxide ions subsequently migrate through the ceramic electrolyte toward the anode, where they undergo oxidation to produce oxygen and release electrons:

$$\text{Anode: } O^{2-} \rightarrow \tfrac{1}{2}O_2 + 2e^- \quad (8)$$

The electrons generated at the anode are transferred through the external electrical circuit to the cathode, completing the electrochemical process. Because the electrolyzer operates at elevated temperatures, a portion of the energy required for water splitting can be supplied as heat rather than electricity. This characteristic can provide thermodynamic and efficiency advantages when suitable high-temperature heat sources are available.

Although solid oxide electrolysis remains less technologically mature than alkaline and PEM systems, it has considerable potential for high-efficiency hydrogen production, particularly when integrated with industrial processes that provide suitable heat streams [18]. The technology can potentially be coupled with processes such as methanol, dimethyl ether, and ammonia synthesis, enabling effective utilization of available thermal energy and improving overall process integration [2]. However, widespread commercialization remains constrained by challenges associated with electrode and electrolyte degradation, thermal cycling, sealing, material compatibility, and long-term stability under demanding operating conditions. Effective thermal management and the development of durable high-performance materials therefore remain important research priorities for improving the reliability and scalability of solid oxide electrolysis [19].

The performance and energy efficiency of water electrolysis are governed by several interconnected factors, including electrolyzer type, operating temperature, pressure, current density, water quality, and the characteristics of the electrical power supplied to the system [20]. Each electrolyzer technology has a distinct operating window and performance profile. For example, PEM electrolyzers generally operate at relatively low temperatures and can respond rapidly to fluctuations in electricity supply, making them well suited to variable renewable-energy sources such as solar and wind. In contrast, solid oxide electrolyzers operate at substantially higher temperatures and can exploit external heat sources to reduce the electrical energy requirement for hydrogen production.

Advanced monitoring and control systems are essential for maintaining electrolyzer operation within its optimum range, particularly when renewable electricity varies rapidly. Such systems can regulate parameters including current, voltage, temperature, pressure, water flow, and gas production to improve efficiency, operational stability, and component lifetime. In addition, electrolyzer performance cannot be considered independently from the remainder of the hydrogen-production chain. Effective integration with renewable-energy generation, electrical or hydrogen storage, water treatment, gas separation, purification, compression, and downstream distribution is necessary to maximize overall system efficiency [21]. Consequently, optimization at the complete system level, rather than solely at the electrolyzer-unit level, is essential for achieving reliable, efficient, and economically viable green hydrogen production.

The capital cost of electrolyzer systems remains an important factor influencing the economic competitiveness of green hydrogen. Current electrolyzer costs are reported to be approximately $1000–1500 per kW of installed capacity, although actual values vary according to the electrolyzer technology, manufacturing scale, system configuration, material requirements, and degree of technological maturity. Reducing these capital costs is essential for improving the economic feasibility of renewable hydrogen and narrowing the cost gap with established fossil-based production routes such as steam methane reforming. Cost targets in the range of approximately $200–300 per kW have therefore been identified as an important benchmark for supporting greater competitiveness and facilitating large-scale deployment.

Electrolyzer efficiency is another critical parameter determining the overall cost and energy requirements of hydrogen production. Existing electrolyzer systems typically achieve efficiencies of approximately 60–70%, indicating that a substantial proportion of the electrical energy supplied to the system is converted into the chemical energy contained in the produced hydrogen [22]. Further improvements in electrical efficiency, together with reductions in capital expenditure, degradation rates, and maintenance requirements, will be necessary to enhance the competitiveness of green hydrogen. Increasing manufacturing scale, improving electrode and membrane materials, optimizing system design, and integrating electrolyzers more effectively with low-cost renewable electricity could collectively contribute to these improvements.

The global installed capacity of water electrolysis for hydrogen production has historically remained relatively limited, although substantial expansion has been observed as investment in renewable hydrogen technologies increases. Earlier estimates placed worldwide electrolysis capacity at approximately 200–300 MW, with major projects concentrated in regions possessing abundant renewable-energy resources, including Europe, North America, and Asia [23]. Continued investment, policy support, manufacturing expansion, and technological improvements are expected to accelerate the deployment of electrolyzer systems in the coming years.

Despite this growth potential, electrolysis has historically represented only a small share of global hydrogen production. Conventional hydrogen generation remains dominated by fossil-fuel-based pathways, particularly steam methane reforming (SMR) of natural gas, which is associated with substantial carbon dioxide emissions. Electrolytic hydrogen has therefore accounted for less than 5% of the global hydrogen market in the context of the cited data. Increasing the contribution of renewable-powered electrolysis is consequently important for reducing the carbon intensity of hydrogen production and supporting broader industrial decarbonization.

A further advantage of water electrolysis is the high purity of the hydrogen product. Depending on the electrolyzer configuration, operating conditions, and downstream gas-treatment system, electrolytic hydrogen can typically achieve purity levels above 99.9%. PEM electrolyzers are particularly capable of producing highly pure hydrogen, with reported purity levels reaching approximately 99.999% under suitable operating conditions [24]. Such high-purity hydrogen can be directly suitable for a wide range of industrial, chemical, and energy applications, potentially reducing the need for extensive downstream purification and improving the overall efficiency of the hydrogen-production system.

The production of green hydrogen through renewable-powered water electrolysis is a rapidly developing technological field, with ongoing research directed toward improving conversion efficiency, lowering capital and operating costs, extending electrolyzer lifetime, and expanding the range of potential applications [25]. Progress in these areas is essential for increasing the competitiveness of electrolytic hydrogen and facilitating its large-scale commercial deployment. At the national level, countries such as Germany, Australia, and Japan have made substantial progress in developing green hydrogen strategies, establishing demonstration and pilot projects, and building the infrastructure required for future hydrogen production and utilization. These initiatives provide important opportunities for evaluating system performance under practical operating conditions and accelerating the transition from laboratory-scale technologies toward commercial deployment.

The broad applicability of electrolytic hydrogen further strengthens its relevance to energy-system decarbonization. Hydrogen generated using renewable electricity can be employed in fuel-cell vehicles, industrial processes, energy storage, power generation, and other applications where direct electrification may be technically or economically challenging [26]. Consequently, the effective integration of electrolyzers with renewable electricity generation is a critical component of green hydrogen system design. The following section examines the integration of solar- and wind-based electricity generation with electrolyzer systems, with particular emphasis on the factors governing energy consumption, production cost, operational performance, system efficiency, and the overall hydrogen-production process.

2.1.4 Solar-Powered Electrolytic Hydrogen Production (PV)

Photovoltaic (PV) electrolysis combines solar photovoltaic electricity generation with water-electrolysis technology to produce hydrogen from renewable energy. In this configuration, photovoltaic cells absorb incident solar radiation and convert it directly into electrical energy through the photovoltaic effect. The resulting electricity is generated as direct current (DC) and can be supplied to an electrolyzer either directly or through suitable power-conditioning equipment [27]. Within the electrolyzer, the electrical energy drives the electrochemical splitting of water into hydrogen and oxygen. The hydrogen generated during this process can subsequently be purified, compressed, and stored for use in applications such as fuel-cell power generation, industrial processes, energy storage, and transportation.

Although the integration of PV systems and electrolyzers provides a potentially low-carbon pathway for hydrogen production, the overall performance of the system is influenced by several interdependent factors. Variations in solar irradiance lead to fluctuations in electrical output, while the efficiency of photovoltaic conversion, power-electronic components, electrolyzer operation, water availability and quality, hydrogen purification, compression, and storage can all affect the final hydrogen yield and production cost [28]. Therefore, appropriate system design, energy-management strategies, and efficient coupling between the PV array and electrolyzer are essential for maximizing hydrogen production and achieving reliable operation.

The PV-electrolysis process begins with the conversion of solar radiation into electricity using photovoltaic panels. Depending on the availability and reliability of the electrical grid, the PV system may be configured as a grid-connected installation or operated as a standalone, off-grid system in locations where grid access is unavailable, unreliable, or economically unfavorable [29]. The electricity generated by the PV array is subsequently supplied to the electrolyzer to drive water-splitting reactions and produce hydrogen.

Because solar power generation varies with changes in solar irradiance, weather conditions, and the day–night cycle, fluctuations in electricity supply can affect electrolyzer operation and hydrogen production. To mitigate these intermittency-related limitations, electrical energy-storage technologies, particularly batteries, can be incorporated into the system to provide a more stable power supply during periods of reduced or unavailable solar generation [30]. However, the addition of energy-storage systems increases capital expenditure, operating requirements, and overall system complexity, thereby influencing the final cost of hydrogen production. Consequently, the efficiency, reliability, and appropriate sizing of the PV generation, energy-storage system, and electrolyzer are critical factors in determining the overall technical performance, economic feasibility, and sustainability of solar-powered hydrogen production [31].

Photovoltaic-powered electrolysis remains a relatively small but rapidly developing component of the global hydrogen-production landscape. The installed capacity of PV-electrolysis systems has historically been limited, although deployment is increasing as investment in renewable hydrogen technologies expands. Available estimates place global capacity in the range of tens to hundreds of megawatts, while hydrogen generated specifically through PV-powered electrolysis represents less than 1% of total hydrogen production. Continued reductions in photovoltaic and electrolyzer costs, together with improvements in system integration, are expected to support further deployment.

Hydrogen produced using PV electricity can achieve very low life-cycle carbon emissions because the electrolysis process itself does not require fossil fuels as an energy source. Nevertheless, emissions associated with the manufacture, transportation, installation, operation, and eventual replacement of photovoltaic modules and electrolyzer components must be considered when evaluating the complete life-cycle performance. Under the cited comparison, production of approximately 1 kg of hydrogen using PV electrolysis can avoid around 10–12 kg of CO_2 emissions relative to conventional hydrogen-production pathways [24].

Another important characteristic of electrolytic hydrogen is its high product purity. Hydrogen generated through PV-electrolysis systems can typically achieve purity levels exceeding 99.99%, depending on the electrolyzer configuration and downstream purification requirements [32]. Such high-purity hydrogen is particularly valuable for applications with stringent gas-quality requirements, including fuel-cell systems, electronics manufacturing, and pharmaceutical and other specialized industrial processes. Consequently, the combination of renewable electricity, low life-cycle emissions, and high hydrogen purity makes PV electrolysis a promising pathway for the development of sustainable hydrogen-production systems.

Following electrolysis, the produced hydrogen generally requires an appropriate purification step to remove residual contaminants and achieve the quality required for downstream applications. Depending on the electrolyzer configuration and operating conditions, the product stream may contain water vapor, traces of oxygen, and other gaseous impurities. Effective purification is particularly important for applications such as fuel cells, electronics, and specialized industrial processes, where even small concentrations of contaminants can adversely affect system performance and durability.

Several separation technologies can be employed to improve hydrogen purity, with the selection depending on the nature and concentration of the impurities, required product specifications, operating pressure, and process economics. Commonly investigated approaches include pressure swing adsorption (PSA), membrane separation, cryogenic distillation, and integrated or hybrid purification systems that combine two or more separation mechanisms [33]. PSA selectively adsorbs impurities under elevated pressure and releases them during subsequent depressurization, whereas membrane systems exploit differences in gas permeability and selectivity to separate hydrogen from other components. Cryogenic separation relies on differences in the thermophysical properties of gases and can be suitable for specific high-throughput applications. Hybrid purification configurations can further improve separation performance by combining complementary technologies.

2.1.5 Wind-Driven Electrolytic Hydrogen Production

In wind-powered electrolysis systems, electricity required for water splitting is supplied by wind turbines, thereby coupling renewable wind generation directly with hydrogen production. The process begins with the assessment and conversion of available wind resources into electrical power [34]. Wind turbines are typically deployed in areas characterized by sufficiently strong and consistent wind conditions, including both onshore and offshore locations. Prior to installation, a detailed wind-resource assessment is performed to determine the suitability of the proposed site and to estimate its potential electricity output. Meteorological instruments, including anemometers and measurement towers, are used to collect long-term information on wind speed, direction, seasonal variation, and other relevant atmospheric parameters [34].

The collected data are used to determine important design parameters, including turbine type, rotor characteristics, hub height, and optimal positioning or orientation, thereby maximizing energy capture under local wind conditions [35]. Based on the resulting resource assessment, suitable sites can be selected for either onshore or offshore wind farms. Offshore installations can offer advantages in regions with stronger and more consistent wind regimes, although they generally involve greater construction, maintenance, and infrastructure requirements. Once electricity is generated, it is supplied to the electrolyzer, where it drives the electrochemical conversion of water into hydrogen and oxygen.

The design, sizing, and operating strategy of the wind turbine system have a direct influence on the amount and stability of electricity available to the electrolyzer [36]. Variations in wind speed can cause fluctuations in electrical generation, which may affect electrolyzer loading, hydrogen output, and overall system efficiency. Consequently, appropriate turbine selection, wind-resource characterization, power-management strategies, and effective integration between the wind farm and electrolyzer are essential for achieving reliable wind-based hydrogen production.

Modern wind turbines incorporate advanced sensing and control technologies that continuously track operating and environmental conditions, including wind speed and direction, enabling automated adjustment of turbine operation to maximize energy capture and maintain safe performance [37]. These systems can regulate parameters such as rotor speed, blade pitch, and generator operation in response to changing wind conditions. In addition, many contemporary wind farms employ centralized supervisory monitoring and control platforms that allow operators to remotely observe and manage multiple turbines, identify operational abnormalities, schedule maintenance, and optimize overall plant performance [38].

Energy-storage technologies can also be integrated with wind farms to improve the utilization and reliability of electricity generated under variable wind conditions. Battery systems, for example, can temporarily store surplus electricity during periods of strong wind generation and subsequently release the stored energy when wind availability decreases or electricity demand increases. In wind-powered hydrogen systems, such storage can help provide a more stable electrical input to electrolyzers, potentially improving operating continuity and reducing fluctuations in hydrogen production. Therefore, the combination of advanced turbine control, remote monitoring, and appropriately designed energy-storage systems can enhance the reliability, flexibility, and overall efficiency of renewable-powered hydrogen production.

Once electricity is generated by wind turbines, it can be supplied directly to electrolyzers to drive the water-splitting reaction and produce hydrogen. Integrating wind-powered electrolysis with the broader energy infrastructure provides an effective means of utilizing surplus electricity generated during periods of strong wind availability. Instead of curtailing excess renewable electricity, the available power can be converted into hydrogen and stored for subsequent use when electricity demand is high or wind generation declines [39]. This approach can help mitigate the intermittency of wind resources while simultaneously transforming variable renewable electricity into a transportable form of chemical energy.

The global deployment of wind-powered electrolysis remains relatively limited but is expanding through demonstration projects and emerging commercial-scale installations. Based on the cited data, the installed capacity associated with hydrogen production from wind-powered electrolysis is estimated to be in the range of hundreds of megawatts worldwide, encompassing both pilot and larger-scale projects. Examples include initiatives such as the NorthH2 project in the Netherlands and the REFHYNE project in Germany. Despite this development, hydrogen produced through wind-powered electrolysis still represents less than 1% of the global hydrogen market [23]. Nevertheless, its environmental potential is substantial. For example, a wind-powered electrolysis facility producing approximately 1000 tonnes of hydrogen annually could potentially avoid around 10,000–12,000 tonnes of CO_2 emissions per year compared with conventional fossil-based hydrogen production.

Hydrogen generated through wind-powered electrolysis can also achieve very high purity, frequently exceeding 99.99%, depending on the electrolyzer configuration and purification requirements. This quality makes the product suitable for a broad range of applications, including fuel cells, industrial processes, energy storage, and specialized technological uses. Consequently, water electrolysis powered by renewable electricity, including photovoltaic and wind-based configurations, represents an important pathway for expanding sustainable hydrogen production. However, technical, economic, infrastructural, and operational challenges remain, particularly those associated with renewable intermittency, electrolyzer utilization, energy storage, capital costs, and system integration. Addressing these challenges while exploiting emerging technological and market opportunities will be essential for improving the efficiency, scalability, and overall contribution of renewable-powered electrolysis to future sustainable energy systems, as summarized in Table 1.

Table 1: Key challenges, potential opportunities, and development priorities associated with hydrogen production through electrolysis-based processes.

Key area	Major limitations	Potential opportunities	Recommended technological approaches	Priority actions
Electrolyzer performance	Limited conversion efficiency associated with catalyst and electrolyte performance	Development of advanced catalytic materials and improved membrane architectures	High-performance catalysts, optimized electrolytes, next-generation membrane configurations, and AI-assisted operational optimization	Increase R&D funding, accelerate technology scale-up, and validate innovations through pilot-scale demonstrations
Variability of renewable power	Fluctuating solar and wind generation can cause unstable electrolyzer operation	Coupling electrolyzers with energy-storage technologies and flexible renewable-power management	Flexible electrolyzer operation, advanced storage, smart-grid integration, and AI-enabled renewable-energy forecasting	Develop intelligent grid infrastructure and establish regulatory and market incentives for flexible hydrogen production
Economic competitiveness	High capital and operating expenses limit the competitiveness of green hydrogen	Large-scale production, process automation, and improved operational efficiency can reduce costs	Automated process control, optimized plant operation, and economies of scale	Strengthen collaboration between industry and research institutions and provide targeted financial support for cost-reduction technologies
Infrastructure expansion	Insufficient dedicated infrastructure and limited deployment at commercial scale	Standardized, modular systems can facilitate rapid deployment and create new hydrogen business models	Modular electrolyzer systems, standardized infrastructure, digital twins, and predictive-maintenance platforms	Promote strategic investment and strengthen public–private partnerships for infrastructure development
Material durability	Corrosion, material degradation, and limited component lifetime can reduce system reliability	Advanced materials can improve durability while reducing maintenance requirements	Corrosion-resistant materials, advanced catalysts, durable membranes, and protective coatings	Encourage interdisciplinary research, long-duration testing, and pilot projects focused on material performance and system reliability

2.2 Hydrogen Generation via Bioethanol Reforming

Wet ethanol reforming represents a promising hydrogen-production pathway that utilizes ethanol as a renewable, bio-derived feedstock and can provide an alternative route for developing more sustainable hydrogen-generation systems [40]. In this process, ethanol is reacted with water or steam under elevated-temperature catalytic conditions to promote a series of reforming reactions that convert the carbon-containing feedstock into a hydrogen-rich gaseous mixture [11, 41]. The resulting gas stream generally contains hydrogen together with carbon-containing species and other reaction products, which subsequently require appropriate separation and purification to obtain hydrogen of the desired quality. The overall environmental performance of this pathway depends strongly on the origin of the ethanol, process energy requirements, catalyst performance, and management of carbon-containing by-products. When sustainably produced bioethanol and low-carbon process energy are employed, wet ethanol reforming can offer a potentially lower-emission pathway for hydrogen generation and contribute to the broader development of sustainable energy systems (Figure 4).

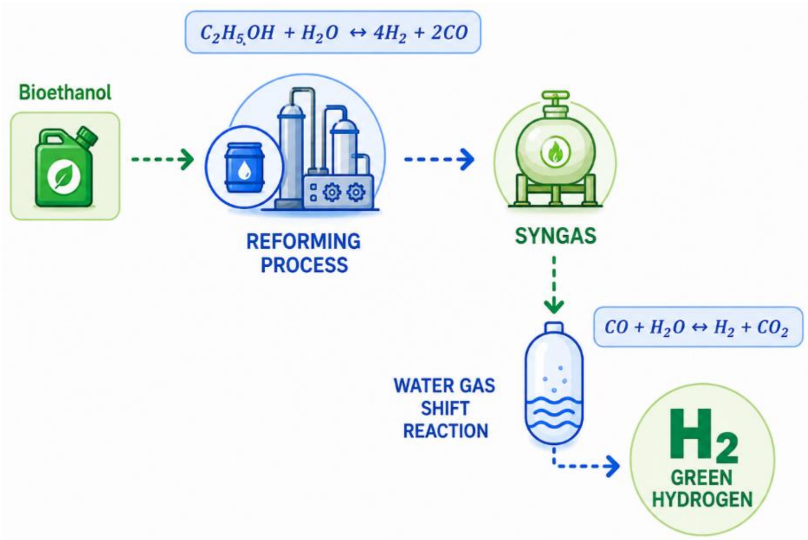

Figure 4: Schematic illustration of the wet ethanol reforming pathway for hydrogen generation, highlighting the conversion of ethanol and steam into a hydrogen-rich product stream.

In the wet ethanol reforming process, liquid ethanol obtained from renewable feedstocks, including biomass-derived resources and bioethanol production pathways, serves as the principal carbon-containing feedstock. The process is typically conducted in a heated reactor or furnace, where controlled temperature and reaction conditions promote the conversion of ethanol in the presence of steam. A suitable heterogeneous catalyst is essential for accelerating the reforming reactions and improving hydrogen yield. Transition-metal-based catalysts, particularly nickel-containing formulations, are widely investigated because of their catalytic activity and comparatively favorable cost.

Under the reforming conditions, ethanol reacts with steam through a sequence of interconnected reactions involving ethanol decomposition, steam reforming, water–gas shift, and related surface reactions. These reactions progressively convert the ethanol feedstock into a hydrogen-rich product gas containing hydrogen and carbon-containing intermediates, including carbon monoxide and carbon dioxide. The composition of the resulting gas depends on parameters such as reaction temperature, steam-to-ethanol ratio, catalyst composition, and residence time. Subsequent gas-cleaning and separation stages are therefore required to remove carbon-containing species and other impurities and to obtain hydrogen with the purity required for downstream applications.

The wet ethanol reforming pathway proceeds through a sequence of catalytic reactions that convert ethanol and steam into a hydrogen-rich gas mixture. A simplified representation of the primary steam-reforming reaction can be expressed as:

$$C_2H_5OH + H_2O \rightarrow 4H_2 + 2CO \quad (9)$$

The carbon monoxide generated during ethanol reforming can subsequently participate in the water–gas shift reaction. In this step, additional steam reacts with carbon monoxide to form hydrogen and carbon dioxide, thereby increasing the overall hydrogen yield:

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (10)$$

The composition and purity of the resulting hydrogen depend on factors such as catalyst formulation, reaction temperature, steam-to-ethanol ratio, residence time, and downstream gas-separation processes. Hydrogen produced through ethanol reforming can typically achieve purity levels of approximately 98–99.9%, although additional purification may be required for applications with stringent hydrogen-quality requirements. The principal carbon-containing by-product is carbon dioxide, accompanied by smaller quantities of other gaseous species depending on the reaction conditions and catalyst performance. Appropriate purification and separation technologies can subsequently be employed to obtain hydrogen at the required specification.

An important advantage of ethanol reforming is its potential compatibility with existing ethanol-production infrastructure. Integration with established bioethanol facilities could enable the reuse of existing processing equipment, feedstock supply chains, utilities, and associated infrastructure, potentially reducing the barriers to implementation and allowing facilities to support both ethanol and hydrogen production [42]. From a carbon-balance perspective, the overall environmental benefit depends strongly on the origin and life-cycle characteristics of the ethanol feedstock. When ethanol is produced from sustainably cultivated biomass, carbon dioxide released during hydrogen production may be partially or substantially balanced by carbon dioxide uptake during biomass growth [43]. Under the cited assessment, producing approximately 1 kg of hydrogen through ethanol reforming may avoid around 10–12 kg of CO_2 emissions compared with conventional steam methane reforming, although the actual reduction depends on feedstock production, process energy, and complete life-cycle emissions [44].

Despite its potential as an alternative hydrogen-production pathway, wet ethanol reforming continues to face several technical and system-level challenges that require further research and development. Catalyst performance is particularly important because the activity, selectivity, stability, and resistance to deactivation directly influence hydrogen yield and process efficiency. The development of highly active and durable catalysts is therefore essential for improving reaction kinetics and minimizing undesirable side reactions. In particular, carbon deposition or coke formation on catalyst surfaces can block active sites, reduce catalytic activity, and shorten catalyst lifetime. Consequently, effective strategies for suppressing carbon formation and maintaining long-term catalyst stability remain important research priorities.

Further optimization of operating conditions, including reaction temperature, steam-to-ethanol ratio, pressure, residence time, and catalyst composition, is also required to improve hydrogen productivity while minimizing energy consumption and unwanted by-products. Process intensification, heat recovery, and improved reactor design could further enhance the overall energy efficiency and environmental performance of the technology.

The organization of ethanol supply and production represents another important consideration for large-scale implementation. Both decentralized and centralized ethanol-production models are currently used, although increasing industrial consolidation has encouraged greater centralization in some regions. Determining the most appropriate configuration for hydrogen production requires a comprehensive supply-chain assessment rather than consideration of production technology alone. Factors such as feedstock availability, transportation distance, infrastructure requirements, capital and operating costs, energy consumption, carbon emissions, and regional resource distribution should be evaluated simultaneously. A systematic comparison of centralized and decentralized configurations can therefore help identify the most economically viable, environmentally sustainable, and operationally efficient model for large-scale hydrogen production, as summarized in Table 2.

The large-scale deployment of green hydrogen through bioethanol wet reforming will depend on a coordinated effort to address existing technological, economic, and environmental limitations while exploiting emerging opportunities. Continued advances in catalyst development can improve reaction activity, selectivity, resistance to deactivation, and long-term stability, while optimization of reactor configurations and operating conditions can enhance hydrogen yield and overall process efficiency. Greater utilization of sustainably produced renewable feedstocks, together with improved heat integration and process-energy management, could further strengthen the environmental performance of the technology. If these developments are supported by appropriate supply-chain strategies and favorable economic conditions, hydrogen production through ethanol wet reforming could become an important complementary pathway within future low-carbon energy systems. Its potential to combine renewable feedstocks with established processing infrastructure makes this technology particularly relevant to efforts aimed at reducing fossil-fuel dependence and advancing a more sustainable and decarbonized energy future.

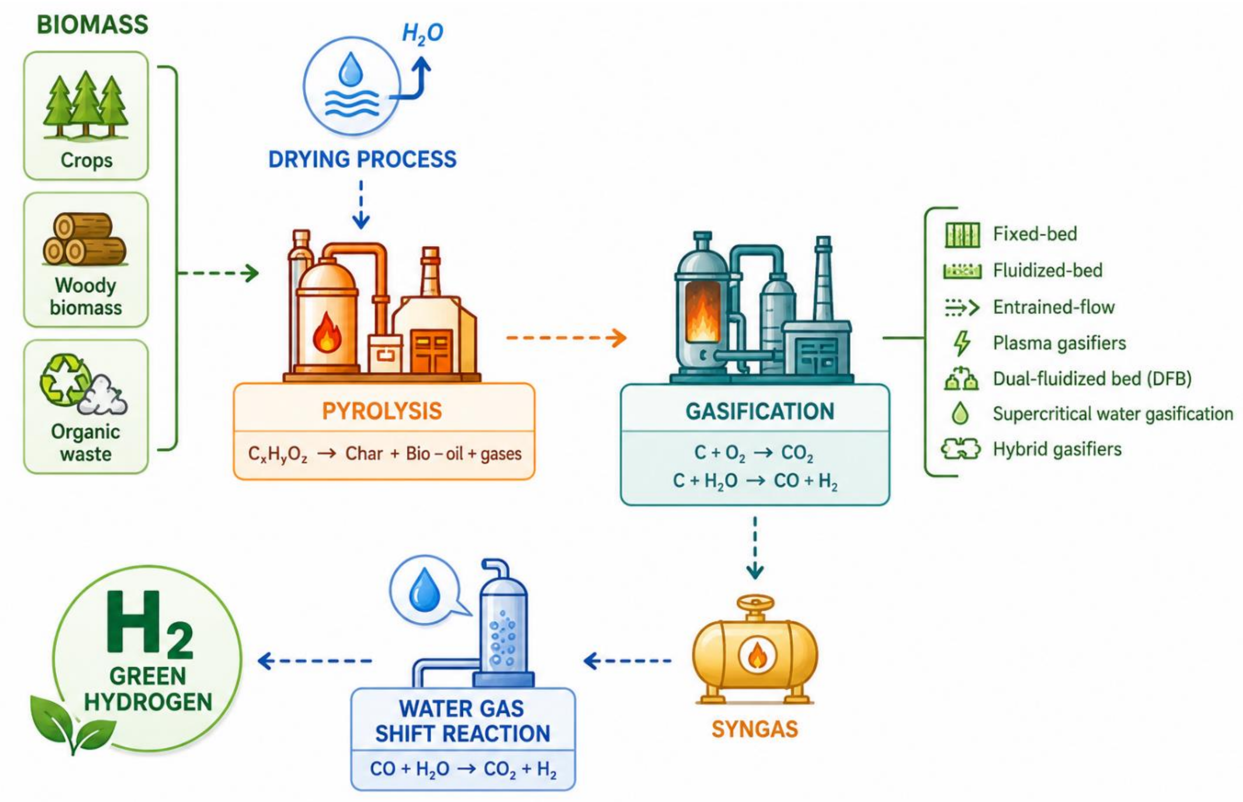

Figure 5: Schematic representation of hydrogen generation from biomass gasification, showing the principal thermochemical conversion stages from biomass feedstock to hydrogen-rich syngas.

Table 2: Major technical, economic, environmental, and operational challenges, together with emerging opportunities for advancing hydrogen production through bioethanol steam reforming.

Strategic aspect	Principal challenge	Development opportunity	Potential technological pathway	Required measures
Process performance and thermal management	Achieving high process efficiency while effectively managing heat and optimizing thermodynamic conditions	Process intensification and improved thermal integration can enhance overall efficiency	Advanced catalysts, optimized reactor configurations, and improved heat-management systems	Increase R&D support, establish pilot-scale demonstrations, and strengthen industry–academia collaboration
Renewable feedstock integration	Variability in the availability and characteristics of renewable feedstocks	Standardized feedstock supply chains and improved pre-treatment can provide more consistent raw materials	Advanced pre-treatment, real-time feedstock monitoring, and optimized feedstock conditioning	Develop cooperation with biofuel industries, establish feedstock-quality guidelines, and promote standardized sourcing practices
Technological integration and infrastructure	Difficulty in integrating new hydrogen technologies with existing infrastructure	Retrofitting existing facilities and adopting modular configurations can accelerate deployment	Modular reactors, advanced process-control systems, and integrated infrastructure optimization	Increase infrastructure investment, develop standardization protocols, encourage public–private partnerships, and provide regulatory support
Decentralized hydrogen applications	Logistical constraints, distribution difficulties, and regulatory barriers associated with decentralized production	Localized production and innovative hydrogen storage/distribution systems can reduce transportation requirements	On-site electrolysis, mobile hydrogen infrastructure, and advanced storage and distribution technologies	Establish supportive regulations, invest in decentralized infrastructure, and promote continued innovation in hydrogen storage and logistics

2.3 Biomass-to-Hydrogen Gasification Pathway

Biomass gasification is a thermochemical conversion process in which biomass feedstocks, including wood, agricultural residues, forestry resources, and selected organic wastes, are transformed into a combustible gas mixture known as synthesis gas or syngas. The process is carried out under controlled operating conditions with a restricted supply of oxygen or another gasifying agent, thereby limiting complete combustion and promoting the conversion of the organic feedstock into gaseous products. The resulting syngas typically contains hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), water vapor, and smaller quantities of other gaseous compounds, with its composition depending on the biomass characteristics and gasification conditions [45].

Biomass gasification has attracted attention as a potential pathway for renewable hydrogen production because it can utilize locally available biological resources and organic residues while simultaneously generating a versatile intermediate gas. The resulting syngas can be processed through additional reactions, separation, and purification steps to increase its hydrogen content and obtain hydrogen suitable for downstream applications. Beyond hydrogen generation, syngas can also be utilized for combined heat and power production or as a feedstock for the synthesis of fuels and chemicals. When sustainably sourced biomass is used and carbon emissions throughout the complete life cycle are appropriately managed, biomass gasification may offer the potential for low-net-carbon or near-carbon-neutral energy production. These characteristics make it a potentially valuable component of integrated renewable-energy and circular-resource systems (Figure 5).

Organizations such as the International Energy Agency (IEA), the U.S. Department of Energy (DOE), and other international energy institutions provide valuable information regarding technological developments, deployment trends, and the evolving role of biomass gasification in hydrogen production [46]. The overall conversion process involves several interconnected stages that determine the composition and quality of the resulting syngas. These stages generally include biomass drying, pyrolysis, gasification, post-gasification water–gas shift conversion, and the formation or removal of tar and soot (Figure 5). During drying, moisture is removed from the feedstock to improve the thermal efficiency of subsequent conversion stages. Pyrolysis then thermally decomposes the biomass in the absence of sufficient oxygen, producing gases, condensable compounds, and solid char. The gasification stage subsequently converts these products into a hydrogen-rich syngas under controlled thermochemical conditions. The water–gas shift reaction can then be employed to increase hydrogen production by converting carbon monoxide and steam into additional hydrogen and carbon dioxide.

A variety of gasifier configurations have been developed to accommodate different biomass characteristics, operating conditions, and production scales. Major technologies include fixed-bed gasifiers, fluidized-bed gasifiers, entrained-flow gasifiers, plasma gasifiers, dual-fluidized-bed (DFB) gasifiers, supercritical-water gasification systems, and hybrid gasification configurations. Each technology exhibits distinct advantages and limitations in terms of operating temperature, feedstock flexibility, heat and mass transfer, syngas composition, tar formation, scalability, and overall process efficiency. The selection of an appropriate gasification technology therefore depends on feedstock properties, desired hydrogen yield, process scale, energy requirements, environmental performance, and downstream gas-cleaning and purification requirements.

Fixed-bed gasifiers represent one of the comparatively simple and well-established configurations used for thermochemical conversion of biomass. In these systems, biomass is generally introduced through the upper portion of the reactor, while air, oxygen, steam, or a combination of gasifying agents is supplied at a controlled rate through the reactor. The direction of gas and solid movement determines the principal operating configuration and strongly influences syngas composition, thermal behavior, and tar formation.

In an updraft gasifier, the biomass generally moves downward while the gasifying agent enters from the lower region and the produced syngas flows upward before leaving near the top of the reactor. Char and ash are removed from the lower section. Although this configuration can provide effective thermal utilization, the resulting syngas commonly contains relatively high concentrations of tar because the product gas passes through cooler regions containing pyrolysis products. In contrast, a downdraft gasifier directs the biomass and gasifying medium generally in the same downward direction, with the product gas leaving from the lower portion of the reactor. This arrangement allows volatile compounds and tar precursors to pass through high-temperature reaction zones, promoting greater tar cracking and consequently producing a comparatively cleaner syngas. Char and ash are also discharged from the lower section.

Fluidized-bed gasifiers are particularly attractive for medium- and large-scale biomass conversion because they provide intensive mixing between the feedstock and the gasifying medium, resulting in relatively uniform temperature distributions and effective heat and mass transfer. In these systems, biomass particles are introduced into a bed of fine inert material, commonly sand, which is suspended by an upward flow of gas. Bubbling fluidized-bed (BFB) gasifiers maintain a relatively stable fluidized bed and provide effective contact between biomass, gasifying agents, and hot bed material. Circulating fluidized-bed (CFB) gasifiers operate at higher gas velocities, entraining solid particles into the gas stream and subsequently recirculating them, thereby improving mixing, conversion, and heat-transfer characteristics.

Entrained-flow gasifiers operate at substantially higher temperatures, commonly above 1200 °C, which promotes rapid conversion of biomass and extensive cracking of tar and other hydrocarbons, resulting in comparatively clean syngas. However, these systems generally require carefully prepared and finely divided feedstocks and can involve high energy and capital requirements. Plasma gasification employs extremely high temperatures generated by plasma torches, potentially reaching several thousand degrees Celsius, to promote extensive decomposition of complex biomass components and contaminants. Although this approach can produce a relatively clean synthesis gas and accommodate diverse feedstocks, the substantial electricity demand associated with plasma generation can reduce overall process efficiency.

Dual-fluidized-bed (DFB) gasifiers employ two interconnected reactors, typically separating the gasification and combustion functions. This configuration allows heat to be supplied indirectly to the gasification reactor while limiting direct contact between the biomass and combustion gases. Consequently, DFB systems can provide greater control over syngas composition and facilitate the production of hydrogen-rich gas with reduced dilution by nitrogen when steam is used as the gasifying agent. These characteristics make DFB technology particularly attractive for hydrogen-oriented applications.

Supercritical-water gasification (SCWG) is an emerging approach designed primarily for wet biomass feedstocks.

Under supercritical water conditions, organic material can be converted into a hydrogen-rich gaseous product without requiring extensive feedstock drying. However, the technology remains comparatively immature and faces significant challenges associated with high operating temperatures and pressures, corrosion, reactor materials, and process economics.

Finally, hybrid gasification systems combine two or more conversion technologies to exploit their complementary advantages. For example, integration of fluidized-bed and plasma-based processes can potentially improve biomass conversion, enhance syngas quality, and reduce tar formation. The selection of a particular gasification technology depends on feedstock characteristics, desired hydrogen yield and syngas quality, process scale, energy requirements, environmental performance, and economic considerations [47, 48].

Drying constitutes an essential pretreatment stage in biomass gasification because it reduces the moisture content of the feedstock before the subsequent thermochemical conversion steps. A high initial moisture content can adversely affect gasification performance because a considerable fraction of the supplied thermal energy is consumed in heating and vaporizing the water rather than promoting the conversion of biomass into useful gaseous products. Consequently, excessive moisture can decrease thermal efficiency, alter syngas composition, increase the energy demand of the process, and potentially reduce overall hydrogen productivity.

Two conventional approaches are commonly employed for moisture removal: natural drying and forced-air drying. In natural drying, biomass is exposed to ambient environmental conditions, allowing moisture to evaporate through solar heating and natural air circulation. This approach requires relatively little external energy and can therefore be economically attractive, particularly where sufficient land and favorable climatic conditions are available. However, its effectiveness depends strongly on weather conditions, ambient humidity, solar radiation, and airflow, making the process comparatively slow and difficult to control.

Forced-air drying provides a more controllable alternative in which heated or ambient air is circulated through the biomass using fans, blowers, or other mechanical systems. The increased airflow enhances moisture transfer from the biomass and allows drying conditions to be regulated more effectively. Although this method generally provides greater control and shorter drying times, it requires additional equipment and energy, which can increase the operating cost of the gasification process.

Temperature is an important operating parameter during biomass drying and is commonly maintained within approximately 50–100 °C, depending on the characteristics of the feedstock and the selected drying configuration [49]. The appropriate drying temperature and residence time depend on several factors, including biomass species, particle size, initial moisture content, porosity, and the drying technology employed. Excessively high temperatures should be avoided because they may initiate undesirable thermal decomposition of biomass components before the intended pyrolysis and gasification stages, potentially affecting feedstock quality and reducing the efficiency of subsequent conversion processes.

Therefore, effective moisture management requires an appropriate balance between drying efficiency, energy consumption, process duration, and preservation of biomass properties. Selection of the drying technique and operating temperature should be based on the specific characteristics of the available feedstock and the requirements of the downstream gasification system. Continued research into advanced drying configurations, waste-heat utilization, solar-assisted drying, and energy-efficient moisture-removal technologies could further reduce the energy penalty associated with pretreatment and improve the overall sustainability and efficiency of biomass gasification systems [50].

The second major stage in the biomass gasification sequence is pyrolysis, a thermochemical conversion process in which the dried biomass is heated under oxygen-deficient or oxygen-free conditions. Unlike combustion, the absence of sufficient oxygen prevents extensive oxidation of the feedstock and allows the complex organic constituents of biomass to decompose into a mixture of solid, liquid, and gaseous products. Pyrolysis therefore serves as an important intermediate step in the conversion of biomass into syngas and ultimately hydrogen.

During pyrolysis, the major structural components of biomass—cellulose, hemicellulose, and lignin—undergo thermal decomposition through a series of primary and secondary reactions. As temperature increases, these macromolecular constituents break down into smaller and more volatile molecules. The resulting products are generally classified into three major fractions: solid char, condensable liquid products (bio-oil or tar), and non-condensable gases. The relative proportions of these products depend strongly on factors such as biomass composition, heating rate, reaction temperature, residence time, particle size, and reactor configuration.

Cellulose, which represents a major structural component of many lignocellulosic biomass resources, provides a simplified illustration of the pyrolytic decomposition process. Its thermal degradation can be represented schematically as:

$$C_6H_{12}O_6 \rightarrow \text{char} + \text{bio-oil} + \text{gases} \quad (11)$$

The gaseous fraction generated during pyrolysis may contain hydrogen, carbon monoxide, carbon dioxide, methane, and other light hydrocarbons, while the condensable fraction consists of a complex mixture of oxygenated organic compounds. The solid fraction is primarily composed of carbon-rich char containing residual inorganic minerals and unconverted biomass-derived material. During subsequent gasification, these primary pyrolysis products undergo further reactions with steam, carbon dioxide, oxygen, or other gasifying agents, ultimately contributing to the formation of a hydrogen-rich synthesis gas.

The pyrolysis stage is therefore critical in determining the composition and characteristics of the gas entering the subsequent gasification reactions. Careful control of temperature and residence time is required to promote effective biomass conversion while limiting undesirable formation of tar and other compounds that can complicate downstream gas cleaning and hydrogen purification. Understanding and optimizing pyrolysis behavior is consequently essential for improving the overall efficiency, hydrogen yield, and operational reliability of biomass-based hydrogen-production systems.

During biomass pyrolysis, the thermal decomposition of cellulose and other lignocellulosic components produces three principal product fractions: solid char, condensable liquids (bio-oil), and non-condensable gases. The relative quantity and composition of these products depend strongly on the characteristics of the biomass and the operating conditions of the pyrolysis process. As represented by eqn (11), the volatile compounds released during thermal decomposition can subsequently condense to form bio-oil, which consists of a complex mixture of oxygenated organic compounds, including various hydrocarbons and oxygen-containing molecular species.

The formation of tar is an important consideration because these heavy condensable compounds can create operational difficulties in downstream gasification equipment. Tar can condense on reactor walls, pipelines, filters, heat exchangers, and other components, potentially causing blockage, fouling, and reduced process efficiency. Consequently, the suppression, thermal cracking, catalytic conversion, and downstream removal of tar remain important areas of research in biomass gasification. The composition and yield of bio-oil are influenced by several parameters, particularly pyrolysis temperature, heating rate, biomass composition, particle size, and residence time.

In addition to char and condensable products, pyrolysis generates a gaseous fraction containing carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), and other volatile organic compounds. These gases subsequently participate in the reactions occurring during gasification and contribute to the composition of the final synthesis gas. Their formation and subsequent conversion are therefore directly relevant to hydrogen yield and the overall efficiency of biomass-to-hydrogen conversion.

Pyrolysis is generally conducted at temperatures of approximately 500–800°C, although the optimum operating range depends on the feedstock and reactor configuration. Temperature has a particularly strong influence on product distribution. Relatively lower temperatures generally promote the formation of condensable liquid products, whereas increasing the temperature favors secondary cracking reactions and enhances the formation of permanent gases. The heating rate also plays a significant role in determining the distribution of pyrolysis products. Rapid heating can accelerate the decomposition of biomass and often promotes greater production of gaseous products, whereas slower heating may increase the formation of char and certain condensable fractions [51]. Therefore, precise control of temperature, heating rate, and residence time is essential for directing pyrolysis toward the desired product distribution and improving the subsequent performance of the gasification process.

The subsequent stage in the biomass conversion pathway is gasification, a high-temperature thermochemical process that converts the solid carbonaceous products generated during pyrolysis into a combustible gaseous mixture known as syngas (synthesis gas). The principal objective of gasification is to maximize the conversion of char and other carbon-rich intermediates into gaseous products, particularly hydrogen and carbon monoxide. Depending on the operating conditions, the resulting syngas may contain H_2, CO, CO_2, CH_4, water vapor, and smaller quantities of hydrocarbons and other trace compounds. Because of its chemical versatility, syngas can serve as an intermediate for hydrogen production, heat and power generation, chemical synthesis, and biofuel production.

The gasification reactions involve complex interactions among carbonaceous solids, steam, oxygen, carbon dioxide, and the gaseous products formed during conversion. Two representative reactions can be expressed as:

$$C + O_2 \rightarrow CO_2 \quad (12)$$

$$C + H_2O \rightarrow CO + H_2 \quad (13)$$

Reaction (12) represents the oxidation of carbon and releases heat that can contribute to sustaining the endothermic gasification reactions. Reaction (13) represents the water–gas reaction, in which carbon reacts with steam to generate carbon monoxide and hydrogen. Additional reactions, including methanation, methane reforming, and carbon monoxide conversion, influence the final syngas composition. Consequently, the overall process involves a network of simultaneous and sequential reactions rather than a single chemical transformation.

Gasification is generally performed at elevated temperatures, typically within the range of approximately 700–1500 °C, with the optimum operating temperature depending on the feedstock, reactor configuration, and desired syngas characteristics. Increasing the gasification temperature generally promotes more extensive conversion of solid carbon and favors the formation of gaseous products while reducing the formation of some heavier condensable compounds. Gasification may be performed at atmospheric or elevated pressure, and pressurized operation is of particular interest for applications where downstream synthesis or hydrogen-processing equipment operates under pressure.

The selection of the gasifying agent is another important parameter governing syngas composition. Depending on the process design, oxygen, air, steam, or combinations of these agents can be employed. Air-based gasification is relatively simple and economical but introduces nitrogen into the product gas, thereby diluting the hydrogen and other combustible components. Oxygen-based gasification can produce a more concentrated syngas but requires an oxygen-supply system, which increases process complexity and energy consumption. Steam gasification is particularly attractive for hydrogen-oriented applications because it can promote hydrogen formation without introducing nitrogen into the syngas.

Incomplete conversion of biomass and char can result in the formation of tar, particulates, and unconverted carbonaceous material. These contaminants can cause fouling, blockage, catalyst deactivation, and operational difficulties in downstream equipment. Consequently, gas cleaning and conditioning are important components of biomass-to-hydrogen systems. The final composition of syngas depends on numerous variables, including biomass type and composition, moisture content, gasification temperature and pressure, residence time, reactor design, and the selected gasifying agent.

For hydrogen production, gasification conditions can be specifically optimized to increase the hydrogen concentration while minimizing undesirable compounds. Subsequent gas-conditioning operations, particularly the water–gas shift reaction and gas purification, can further increase hydrogen yield and product quality. Thus, biomass-derived syngas represents a versatile intermediate that can be directed toward hydrogen production, combined heat and power generation, chemical synthesis, and the production of renewable fuels, making gasification an important thermochemical pathway within integrated biomass-based energy systems [52].

Following the primary gasification stage, the resulting syngas commonly contains a considerable fraction of carbon monoxide (CO). For hydrogen-oriented applications, the water–gas shift (WGS) reaction can be employed to convert CO into additional hydrogen while simultaneously reducing the CO concentration in the gas stream. This reaction is particularly important when a high hydrogen concentration is desired and is generally carried out after gasification as part of the syngas-conditioning stage [53]. The overall reaction can be represented as:

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (14)$$

In the WGS process, carbon monoxide reacts with steam to produce carbon dioxide and additional hydrogen. The reaction can therefore increase the hydrogen content of the syngas while converting CO into a more readily manageable carbon-containing product. The extent of conversion depends on parameters such as temperature, steam-to-CO ratio, catalyst characteristics, and residence time. Appropriate WGS operation, followed by downstream purification, can substantially improve the suitability of biomass-derived syngas for high-purity hydrogen production.

A major technical challenge associated with biomass gasification is the formation of tar and soot, both of which can adversely affect gasifier performance and downstream processing. Tar comprises a complex mixture of condensable hydrocarbons and oxygen-containing organic compounds generated primarily through the pyrolysis and incomplete conversion of biomass. When the syngas temperature decreases, these compounds can condense on reactor walls, pipelines, filters, heat exchangers, and other process components. Such deposition can cause fouling, blockage, pressure losses, catalyst deactivation, and reduced heat-transfer efficiency, thereby compromising the reliability and operational performance of the gasification system [54].

Several approaches can be employed to control and remove tar. Catalytic reforming, for example, promotes the conversion of tar compounds into lighter gases and can simultaneously increase the concentration of useful gaseous products. Thermal cracking at sufficiently high temperatures can also decompose heavy hydrocarbons, while filtration and other physical separation techniques can remove condensed or particulate-associated tar. In advanced systems, integrated gas-cleaning configurations combining hot-gas filtration, catalytic tar reforming, and other conditioning technologies can reduce contaminant concentrations before the syngas enters downstream hydrogen-production units.

Soot, in contrast, consists predominantly of very fine carbonaceous particles that can form under conditions of incomplete conversion, particularly during pyrolysis and gasification. Its formation can be influenced by factors such as temperature, equivalence ratio, feedstock properties, gas residence time, and the availability of gasifying agents. Insufficient residence time or unfavorable reaction conditions can prevent complete conversion of carbonaceous intermediates and promote particulate formation [55].

Soot control therefore requires careful optimization of gasification conditions to promote effective carbon conversion. Maintaining appropriate temperature, gasifying-agent ratios, and residence time can help minimize the formation of carbonaceous particulates. In addition, downstream cyclones, hot-gas filters, particulate separators, and other gas-cleaning systems can be incorporated to remove residual soot and ash from the syngas. Effective management of both tar and soot is consequently essential for protecting downstream equipment, improving syngas quality, and achieving efficient and reliable biomass-derived hydrogen production.

Hydrogen production through biomass gasification currently represents a relatively small component of the global hydrogen sector when compared with established pathways such as steam methane reforming (SMR) and renewable-powered water electrolysis. Most biomass-gasification hydrogen projects remain at the pilot or demonstration stage, while only a limited number have progressed toward commercial-scale operation. The installed capacity associated with hydrogen production from biomass gasification is estimated to be in the range of tens of megawatts, although continued research, process optimization, and investment are expected to support future scale-up. Consequently, hydrogen derived from biomass gasification currently accounts for less than 1% of global hydrogen production, while fossil-fuel-based routes, particularly natural-gas-based SMR, continue to dominate the market.

The environmental performance of biomass gasification is strongly dependent on the origin and sustainability of the biomass feedstock, process energy requirements, and management of carbon-containing products and emissions. When biomass is sustainably cultivated or derived from agricultural and forestry residues, carbon dioxide released during thermochemical conversion can be partially balanced by the carbon dioxide absorbed during biomass growth. However, this carbon balance should be evaluated using a complete life-cycle assessment that considers cultivation, harvesting, processing, transportation, gasification, hydrogen purification, and associated energy consumption. Under the cited assessment, production of approximately 1 kg of hydrogen through biomass gasification can potentially avoid 10–12 kg of CO_2 emissions compared with conventional fossil-fuel-based hydrogen production [23].

The purity of hydrogen obtained from biomass gasification depends strongly on the gasification conditions and the effectiveness of downstream syngas cleaning and purification. The raw gas produced by gasification contains hydrogen together with CO, CO_2, methane, water vapor, tar, particulates, and other trace contaminants. After appropriate gas conditioning and purification, hydrogen purity can typically reach approximately 99–99.9% [24]. Advanced separation technologies, including pressure swing adsorption (PSA) and membrane-based separation, can further improve hydrogen purity when higher specifications are required.

Hydrogen at approximately 99% purity can be adequate for numerous industrial applications, including chemical manufacturing and petroleum refining. For applications with more stringent purity requirements, additional purification stages may be necessary to remove residual carbon monoxide, hydrocarbons, moisture, and other contaminants. Therefore, the development of efficient gas-cleaning and hydrogen-separation systems is essential for improving the technical performance, economic feasibility, and broader applicability of biomass-gasification-based hydrogen production.

Overall, biomass gasification represents a promising thermochemical pathway for converting renewable carbonaceous resources into useful gaseous energy carriers. One of its principal advantages is the ability to utilize a broad range of renewable feedstocks, including wood, agricultural residues, forestry by-products, and selected organic wastes. When sustainably sourced biomass is used and the associated carbon flows are appropriately managed, the process has the potential to achieve low net greenhouse-gas emissions. In addition, the syngas generated through gasification is a flexible intermediate that can be directed toward hydrogen production, heat generation, electricity production, chemical synthesis, and renewable-fuel production.

Despite these advantages, several barriers continue to restrict the large-scale deployment of biomass-gasification systems. Variations in feedstock composition, moisture content, particle size, ash content, and availability can significantly influence gasification behavior and syngas quality. The process also involves complex interactions among drying, pyrolysis, gasification, reforming, and gas-cleaning reactions, requiring careful control of operating conditions. Furthermore, the formation of tar, soot, particulates, and other contaminants can increase the complexity and cost of downstream gas conditioning and hydrogen purification. Economic factors, including feedstock logistics, capital investment, energy consumption, catalyst requirements, maintenance, and transportation costs, must also be considered when assessing commercial feasibility.

Continued research and development are therefore focused on improving reactor design, optimizing gasification conditions, developing durable catalysts, reducing tar and particulate formation, enhancing syngas cleaning, and improving hydrogen recovery and purification. Integration with existing biomass-processing facilities, renewable-energy systems, waste-management networks, and carbon-management strategies may further improve the overall sustainability and economic performance of the technology. Accordingly, biomass gasification has the potential to become an important component of future low-carbon energy systems, particularly in regions with abundant sustainable biomass resources. The principal challenges and opportunities associated with biomass gasification are summarized in Table 3.

Table 3: Key challenges and emerging opportunities associated with biomass gasification for sustainable hydrogen production, considering technological, economic, environmental, and operational aspects.

Aspect	Key challenges	Potential opportunities	Technological approaches	Recommended actions
Tar and soot management	Formation of tar and soot can impair gasifier performance, contaminate downstream equipment, and reduce overall system reliability	Effective contaminant control can improve operational stability and extend equipment service life	Advanced filtration, catalytic tar reforming, plasma-assisted conversion, and integrated gas-cleaning systems	Conduct pilot-scale demonstrations and establish appropriate technical and regulatory standards
Feedstock quality and standardization	Variations in biomass composition, moisture, and availability make consistent gasification performance difficult	Better resource utilization can reduce waste disposal and increase the value derived from biomass residues	Flexible gasification systems, advanced sensors, adaptive process control, and feedstock pre-treatment	Establish standardized feedstock specifications, develop adaptive operating protocols, and create comprehensive biomass databases
Economic feasibility	High capital costs, feedstock logistics, and operational expenses can limit the commercial competitiveness of biomass gasification	Cost optimization and expanding hydrogen markets can improve the economic attractiveness of the technology	Process optimization, efficient reactor configurations, advanced catalysts, and cost-effective biomass conversion systems	Conduct techno-economic assessments, support demonstration projects, and introduce appropriate policy and financial incentives
Hydrogen quality and purity	Achieving consistently high-purity hydrogen while maintaining economically viable operation remains challenging	High-quality hydrogen can serve a wider range of industrial, energy, and mobility applications	Advanced gas purification, membrane separation, adsorption processes, selective catalysts, and optimized reactor designs	Increase R&D investment, undertake field validation, and establish harmonized hydrogen-quality standards
Decentralized hydrogen production	Distributed systems face challenges related to logistics, scale, infrastructure, and local resource availability	Localized production can reduce transportation requirements and enable better utilization of regionally available biomass	Compact and modular gasification units, localized gas-cleaning systems, and scalable hydrogen-production configurations	Promote decentralized demonstration projects, strengthen local stakeholder participation, and develop supportive regulatory frameworks
Integration with carbon capture	Capturing and managing CO_2 from biomass gasification requires additional equipment, energy, and investment	Combining biomass gasification with carbon capture can enable low-carbon or potentially carbon-negative hydrogen production	Advanced carbon capture and storage (CCS) systems, optimized gasification–CCS integration, and CO_2 utilization pathways	Increase R&D funding, establish pilot-scale CCS projects, and develop policies supporting integrated biomass gasification and carbon management

2.4 *High-Temperature Thermochemical Hydrogen Pathways*

High-temperature thermochemical cycles have attracted increasing attention as an alternative pathway for sustainable hydrogen production because they utilize thermal energy to drive a sequence of chemical reactions that ultimately split water into hydrogen and oxygen. Unlike conventional electrolysis, these processes can potentially obtain a substantial fraction of the required energy in the form of high-temperature heat, thereby reducing dependence on electrical energy and enabling integration with concentrated solar thermal systems, nuclear heat sources, or other high-temperature renewable and low-carbon energy streams [56]. The cyclic nature of these processes allows the intermediate chemical species to be regenerated and reused, while water serves as the fundamental reactant for hydrogen generation (Figure 6).

Several thermochemical approaches have been investigated, each employing different reaction pathways, operating temperatures, and redox-active materials. Important examples include the sulfur–iodine (S–I) cycle, hybrid sulfur cycle, cerium oxide-based thermochemical cycles, and ferrite-based thermochemical cycles. These technologies differ in their thermodynamic requirements, reaction kinetics, material stability, heat integration potential, and overall process complexity. The S–I and hybrid sulfur cycles rely on sulfur-containing intermediates to facilitate water splitting, whereas metal-oxide-based cycles employ reversible oxidation–reduction reactions to release and subsequently regenerate oxygen and hydrogen [56].

The principal attraction of high-temperature thermochemical hydrogen production lies in its potential for high conversion efficiency when integrated with an appropriate high-temperature heat source. However, practical implementation remains challenging because of demanding operating temperatures, material degradation, corrosion, heat recovery requirements, reaction kinetics, and the need for efficient separation of the products and intermediate chemicals. Consequently, ongoing research is directed toward improving cycle efficiency, developing durable materials, simplifying process configurations, and establishing effective thermal-integration strategies to enable the eventual large-scale production of low-carbon hydrogen through thermochemical water-splitting technologies.

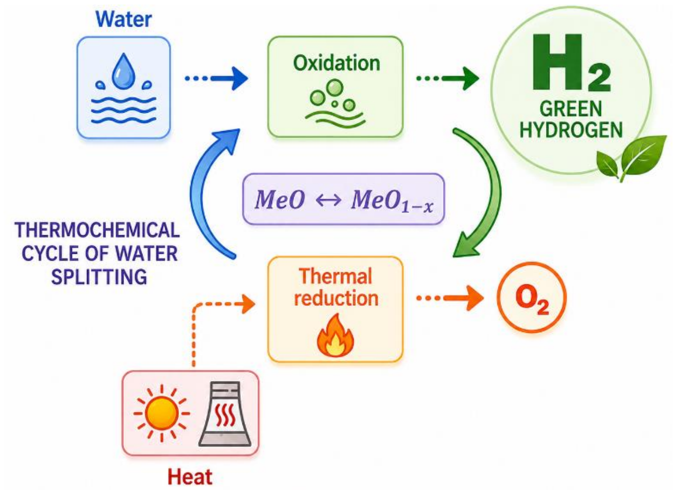

Figure 6: Schematic overview of thermochemical hydrogen-production pathways, illustrating the conversion of water into hydrogen through high-temperature chemical cycles driven by low-carbon heat sources.

2.4.1 Sulfur–Iodine Thermochemical Cycle (S–I)

The sulfur–iodine (S–I) cycle is a high-temperature thermochemical water-splitting process designed to generate hydrogen through a sequence of chemical reactions in which sulfur- and iodine-containing compounds act as recyclable intermediates [55]. The cycle is particularly attractive because water is the net feedstock, while the sulfur and iodine species are regenerated and recirculated within the process. The required thermal energy can potentially be supplied by high-temperature sources such as advanced nuclear reactors or concentrated solar thermal systems, making the S–I cycle a potential pathway for large-scale low-carbon hydrogen production.

The first major stage involves the high-temperature decomposition of sulfuric acid (H_2SO_4). In this step, sulfuric acid is thermally decomposed to produce sulfur dioxide, water, and oxygen:

$$H_2SO_4 \rightarrow SO_2 + H_2O + \tfrac{1}{2}O_2 \qquad (15)$$

This reaction requires substantial thermal energy and is generally associated with temperatures above approximately 830 °C. The high temperature requirement represents one of the defining characteristics of the S–I cycle and creates opportunities for integration with high-temperature nuclear heat or concentrated solar thermal energy. Efficient recovery and utilization of heat from this stage are essential for improving the overall thermal efficiency of the cycle.

The sulfur dioxide generated during sulfuric acid decomposition subsequently participates in the Bunsen reaction, in which sulfur dioxide reacts with iodine and water to form sulfuric acid and hydrogen iodide. A simplified representation of this stage can be expressed through the following reactions:

$$SO_2 + 2H_2O + I_2 \rightarrow H_2SO_4 + 2HI \qquad (16)$$

The products of the Bunsen reaction form two liquid phases that can be separated and processed further. The sulfuric-acid phase is returned to the high-temperature decomposition section, thereby regenerating sulfur dioxide and oxygen, while the hydrogen-iodide phase is directed toward the hydrogen-production stage. The overall cycle therefore relies on effective phase separation and controlled recirculation of the sulfur- and iodine-containing intermediates.

In the final stage, hydrogen iodide undergoes thermal decomposition to produce hydrogen and regenerate iodine:

$$2HI \rightarrow H_2 + I_2 \qquad (17)$$

The iodine generated in this reaction is recycled back into the Bunsen reaction, completing the iodine loop. Similarly, sulfur-containing species are continuously regenerated and returned to the corresponding reaction stages. In this manner, the S–I cycle can accomplish the overall splitting of water into hydrogen and oxygen while minimizing the net consumption of the intermediate chemical species.

The major technical challenge of the S–I cycle is its demanding operating environment, particularly the high temperature required for sulfuric-acid decomposition and the corrosive nature of concentrated sulfuric acid, hydrogen iodide, and iodine-containing mixtures. Therefore, the development of corrosion-resistant materials, efficient heat exchangers, reliable phase-separation systems, and effective process-integration strategies is critical for practical implementation. Nevertheless, the possibility of coupling the S–I cycle with high-temperature renewable or low-carbon heat sources makes it an important candidate for future large-scale hydrogen production.

The Bunsen reaction constitutes a central stage of the sulfur–iodine cycle, in which sulfur dioxide, iodine, and water interact to generate two principal product streams: sulfuric acid and hydrogen iodide. The reaction enables the sulfur- and iodine-containing intermediates to be separated into phases that can subsequently be directed to their respective decomposition steps. The sulfuric acid stream is returned to the high-temperature decomposition stage, while the hydrogen iodide stream is processed further to recover molecular hydrogen. Effective phase separation and control of the reaction conditions are therefore essential for maintaining continuous operation and minimizing cross-contamination between the two process streams.

The hydrogen-production stage involves the thermal decomposition of hydrogen iodide. In this step, hydrogen iodide is dissociated to form hydrogen and iodine:

$$2HI \rightarrow H_2 + I_2 \quad (18)$$

The hydrogen generated in this reaction is recovered as the desired product, whereas the iodine is recycled to the Bunsen-reaction stage. Similarly, sulfur-containing intermediates are continuously regenerated and recirculated, allowing the process to operate as a closed thermochemical cycle. Overall, the net reaction of the sulfur–iodine process corresponds to the decomposition of water into hydrogen and oxygen, with sulfur and iodine acting primarily as recyclable chemical intermediates.

The S–I cycle is particularly attractive for integration with high-temperature heat sources, including advanced nuclear reactors and concentrated solar thermal systems. Such integration allows the substantial thermal energy required for the sulfuric-acid decomposition step to be supplied without relying exclusively on conventional electricity. Unlike conventional water electrolysis, the S–I cycle does not require direct electrochemical splitting of water, thereby avoiding some of the limitations associated with high-temperature electrolyzers and electrode processes.

However, the practical implementation of the S–I cycle remains challenging. The process involves highly corrosive chemical species, including concentrated sulfuric acid, sulfur dioxide, hydrogen iodide, and iodine, in combination with elevated operating temperatures. Consequently, materials compatibility and long-term durability are major considerations in the design of reactors, heat exchangers, piping, separators, and other process components. Materials must maintain their mechanical integrity and corrosion resistance during prolonged exposure to aggressive chemical environments and thermal cycling.

Further development of the technology therefore requires advances in corrosion-resistant materials, reactor configuration, heat-transfer systems, process integration, and thermal-efficiency optimization. Effective recovery and reuse of process heat are particularly important because a significant proportion of the overall energy requirement is associated with high-temperature chemical decomposition. Improvements in these areas could reduce operating costs, increase hydrogen yield, and enhance the overall efficiency and economic competitiveness of the sulfur–iodine cycle as a large-scale low-carbon hydrogen-production pathway.

2.4.2 Hybrid Sulfur Thermochemical Route (HyS)

The Hybrid Sulfur Cycle (HSC) is another thermochemical pathway investigated for low-carbon hydrogen production. Like the sulfur–iodine cycle, the HSC can utilize high-temperature thermal energy from sources such as advanced nuclear systems or concentrated solar thermal technologies [57]. However, the HSC differs from the sulfur–iodine cycle in that it combines high-temperature thermochemical processing with a lower-temperature electrochemical hydrogen-production step. This hybrid configuration can reduce the electrical energy requirement compared with conventional water electrolysis while retaining the potential benefits of high-temperature heat integration.

The process begins with the thermal decomposition of sulfuric acid, which occurs at elevated temperatures and generates sulfur dioxide, water, and oxygen:

$$H_2SO_4 \rightarrow SO_2 + H_2O + \tfrac{1}{2}O_2 \quad (19)$$

This reaction is analogous to the corresponding sulfuric-acid decomposition step in the sulfur–iodine cycle. A substantial amount of thermal energy is required to drive the reaction, making the availability of an efficient high-temperature heat source an important factor in the overall performance of the HSC. The sulfur dioxide generated in this stage is subsequently processed through the sulfur-based reaction pathway, while oxygen is recovered as a co-product.

A subsequent stage involves the conversion or depolarization of sulfur dioxide, in which sulfur dioxide participates in a reaction with hydrogen sulfide to generate elemental sulfur and water:

$$2SO_2 + 2H_2S \rightarrow 3S + 2H_2O \quad (20)$$

This reaction facilitates the regeneration of sulfur-containing intermediates and contributes to closing the chemical cycle. The resulting sulfur can be further processed or recycled within an appropriately integrated system. In the complete HSC configuration, the sulfur dioxide generated during sulfuric-acid decomposition is ultimately regenerated through the downstream electrochemical and chemical reactions, allowing continuous operation with recycling of the sulfur species.

A distinguishing feature of the Hybrid Sulfur Cycle is its use of an electrochemical hydrogen-evolution step rather than relying entirely on high-temperature thermal decomposition of hydrogen-containing intermediates. This configuration can potentially lower the electrical energy demand and permit more effective utilization of available thermal energy. The integration of high-temperature heat with relatively lower-temperature electrochemical processing also provides opportunities for flexible coupling with nuclear and solar-thermal energy systems.

Nevertheless, practical deployment of the HSC requires careful management of corrosive sulfur-containing species, high-temperature reaction environments, and electrochemical components. Reactor materials, electrode and membrane durability, heat recovery, sulfur management, and efficient separation of reaction products are important considerations for long-term operation. Therefore, continued improvements in materials, electrochemical cell design, process integration, heat management, and sulfur-cycle control are required to improve the efficiency, reliability, and economic feasibility of the Hybrid Sulfur Cycle for large-scale sustainable hydrogen production [57].

The third stage of the Hybrid Sulfur Cycle (HSC) involves the conversion of elemental sulfur generated during the sulfur dioxide depolarization step. In this stage, sulfur reacts with water to form sulfuric acid and hydrogen sulfide, thereby regenerating the sulfur-containing intermediates required for continued operation of the cycle. The corresponding reaction can be represented as:

$S + H_2O \rightarrow H_2SO_4 + H_2S$ (21)

The products formed in this reaction subsequently participate in the preceding stages of the cycle. In particular, the regenerated sulfuric acid can be returned to the high-temperature decomposition stage, while hydrogen sulfide participates in the sulfur dioxide depolarization reaction. Through this continuous recycling of sulfur-containing compounds, the chemical intermediates are regenerated rather than being consumed in the overall process.

The complete HSC is established by combining the sulfuric-acid decomposition, sulfur dioxide depolarization, and water-splitting reactions, together with the associated electrochemical hydrogen-production step. When the individual reactions are considered collectively, the sulfur species function primarily as recyclable intermediates, while water serves as the net feedstock. The overall objective is therefore the conversion of water into hydrogen and oxygen, with the sulfur compounds continuously circulated within the process [57].

An important advantage of the HSC is its potential to operate under less severe thermal conditions than some fully thermochemical water-splitting cycles. The combination of high-temperature chemical processing with an electrochemical step provides greater flexibility in matching the process with available heat sources. Consequently, the HSC may be integrated with concentrated solar thermal systems, advanced nuclear reactors, or other suitable low-carbon heat supplies. Such integration can potentially improve energy utilization by assigning high-temperature heat to the reactions that require it while using electricity only where electrochemical conversion is advantageous.

Despite these potential benefits, several technical barriers must be overcome before large-scale implementation becomes feasible. The sulfur-containing reaction environment can be highly corrosive, requiring materials with excellent chemical and thermal stability. Corrosion resistance, component durability, electrochemical performance, heat integration, sulfur management, and overall process efficiency remain important areas of research. In addition, effective separation and recycling of the chemical intermediates are necessary to maintain stable operation and minimize material losses.

Thus, the Hybrid Sulfur Cycle represents a potentially attractive route for sustainable hydrogen production because it combines thermochemical and electrochemical conversion mechanisms and can exploit high-temperature renewable or low-carbon heat sources. Continued advances in materials science, reactor engineering, electrochemical technologies, and thermal-process integration will be essential for improving its efficiency, reliability, and economic competitiveness [57].

2.4.3 Ceria-Based Redox Thermochemical Cycle

The cerium oxide (CeO_2)-based thermochemical cycle is a metal-oxide redox pathway investigated for hydrogen production through cyclic water-splitting reactions. In this approach, cerium oxide functions as a recyclable redox-active material that undergoes repeated changes between its oxidized and reduced states. The process requires appropriately designed reactors and supporting components capable of operating at elevated temperatures while promoting rapid redox reactions, efficient heat transfer, and continuous recycling of the solid material [58].

The operation of the cycle can be broadly divided into reduction, hydrogen-production, and material regeneration stages. During the high-temperature reduction stage, cerium oxide is heated sufficiently to release oxygen from its crystal lattice, producing an oxygen-deficient form of the material commonly represented as CeO_{2-x}. This reduction step requires substantial thermal energy and can be driven using concentrated solar heat or another suitable high-temperature energy source. The generation of oxygen vacancies modifies the redox state of the cerium oxide and prepares the material for subsequent hydrogen generation.

In the hydrogen-production stage, the reduced cerium oxide is exposed to water vapor. The oxygen-deficient oxide reacts with water, extracting oxygen from the water molecules and releasing molecular hydrogen. As a result, the reduced cerium oxide is simultaneously reoxidized toward CeO_2. This cyclic reduction–oxidation mechanism allows the solid oxide to function as an oxygen-transfer medium while hydrogen is produced from water.

The simplified redox behavior can be represented conceptually as:

$CeO_2 \rightarrow CeO_{2-x} + \frac{1}{2}xO_2$
(reduction)

$CeO_{2-x} + xH_2O \rightarrow CeO_2 + xH_2$
(oxidation/hydrogen production)

The exact reaction stoichiometry depends on the degree of oxygen non-stoichiometry achieved during the reduction step. Unlike a conventional one-step chemical reaction, the overall process relies on repeatedly cycling the cerium oxide between its oxidized and oxygen-deficient states. Consequently, the redox material is not consumed overall and can theoretically be reused over many cycles.

A final consideration is the separation and management of the gaseous products. Oxygen released during the high-temperature reduction stage must be effectively separated from the process streams, while hydrogen generated during the water-splitting stage must be recovered without significant contamination by residual water vapor or oxygen. Appropriate gas-separation and recirculation systems are therefore required to maintain product purity and enable continuous operation. The regenerated cerium oxide is subsequently returned to the high-temperature reduction stage, establishing a closed-loop process.

The practical performance of cerium oxide-based cycles depends strongly on reactor design, heat-transfer efficiency, redox kinetics, oxygen transport, and the long-term stability of the oxide. High operating temperatures also create challenges related to thermal management, material durability, and energy consumption. Nevertheless, the ability of cerium oxide to undergo reversible redox transformations makes it an attractive candidate for thermochemical hydrogen production, particularly when coupled with concentrated solar thermal energy [58]. Continued research into reactor configurations, oxygen-vacancy engineering, heat recovery, and strategies for reducing the required reduction temperature could improve the efficiency and scalability of this thermochemical hydrogen-production pathway.

The cerium oxide-based thermochemical cycle can be integrated with concentrated solar thermal energy or high-temperature nuclear heat, providing the substantial thermal input required to drive the redox reactions. Such integration offers the possibility of utilizing low-carbon and potentially abundant energy resources while converting high-temperature heat into chemical energy in the form of hydrogen. In particular, concentrated solar systems can supply the intense thermal energy required during the high-temperature reduction stage, whereas nuclear heat can provide a more continuous thermal input and potentially support stable operation over extended periods.

The selection of cerium oxide (CeO_2) as the redox-active material is associated with its ability to undergo reversible changes between oxidized and oxygen-deficient states. This reversible redox behavior is fundamental to the cyclic operation of the process because the material can release oxygen during the reduction stage and subsequently recover oxygen from water during the hydrogen-generation stage. Unlike a consumable chemical reagent, cerium oxide can therefore be repeatedly regenerated and reused, provided that its structural and chemical stability are maintained over successive cycles.

The reversible absorption and release of thermal energy associated with the redox transformations also provide opportunities for thermal-energy management and storage. Heat generated or available during one operating period can potentially be recovered and stored for subsequent use, improving the utilization of the high-temperature energy input. Such thermal integration may increase process flexibility and help compensate for the intermittency of solar energy. Consequently, coupling the thermochemical cycle with suitable thermal-storage technologies could facilitate more continuous hydrogen production during periods of reduced solar availability or temporary interruptions in the heat supply.

Despite these advantages, material durability remains one of the principal technical challenges. The redox material and reactor components must withstand repeated exposure to high temperatures, oxygen-rich and oxygen-deficient environments, and continuous thermal cycling. Repeated reduction and oxidation can alter the structural characteristics of cerium oxide, potentially affecting its oxygen-storage capacity, reaction kinetics, and long-term hydrogen-production performance. Reactor materials must likewise resist thermal degradation, oxidation, mechanical stresses, and chemical interactions with the reactive process environment.

Therefore, further development of the cerium oxide cycle requires improvements in redox-material stability, reactor materials, heat-transfer design, thermal-energy recovery, and cyclic operation strategies. Enhancing the durability of the active material while maintaining rapid redox kinetics will be particularly important for achieving long operating lifetimes and improving the economic feasibility of thermochemical hydrogen production.

2.4.4 Ferrite-Mediated Thermochemical Redox Cycle

Ferrite-based thermochemical cycles represent another class of metal-oxide redox processes being investigated for sustainable hydrogen production. Compared with more extensively studied thermochemical pathways, ferrite cycles remain at a comparatively earlier stage of technological development. Nevertheless, their ability to undergo reversible oxidation–reduction reactions makes iron-containing oxides attractive as recyclable reaction media for thermochemical water splitting [59]. Ferrites and related iron-oxide materials can repeatedly exchange oxygen with the surrounding environment, enabling the conversion of water into hydrogen while regenerating the solid oxide.

The operation of a ferrite-based cycle can generally be described through alternating high-temperature reduction and water-splitting oxidation stages. In the first stage, ferric oxide is thermally reduced to a lower oxidation state, releasing oxygen from the solid lattice. A simplified representation of this reaction is:

$$Fe_2O_3 \rightarrow 2FeO + \tfrac{1}{2}O_2 \qquad (22)$$

During this high-temperature reduction step, ferric oxide (Fe_2O_3) is converted into ferrous oxide (FeO), accompanied by the release of molecular oxygen. The thermal energy required to drive this transformation can potentially be supplied by concentrated solar thermal systems or other suitable high-temperature heat sources. The reduction stage therefore determines an important portion of the overall energy requirement and strongly influences the efficiency of the thermochemical cycle.

The reduced iron oxide subsequently enters the hydrogen-production stage, where it reacts with water vapor. During this reaction, FeO is reoxidized to Fe_2O_3 while water is reduced to molecular hydrogen:

$$2FeO + H_2O \rightarrow Fe_2O_3 + H_2 \qquad (23)$$

Hydrogen is consequently released as the desired product, while the ferric oxide formed during the reaction can be returned to the reduction stage. This regeneration of the original oxidation state enables the solid material to participate repeatedly in successive reaction cycles.

The oxygen generated during the high-temperature reduction stage must be effectively separated from the process stream to maintain appropriate reaction conditions and prevent contamination of the hydrogen product. A gas-separation and recirculation system can be incorporated to manage the oxygen-containing stream and facilitate closed-loop operation. Continuous recycling of the iron-oxide material is central to the process because the ferrite functions as a reaction intermediate rather than a net reactant.

The principal attraction of ferrite-based cycles is the relatively simple redox mechanism and the potential availability and comparatively low cost of iron-containing materials. However, practical implementation is constrained by the high temperatures required for reduction, reaction kinetics, material sintering, changes in redox activity during repeated cycling, and the need for efficient heat and mass transfer. The long-term stability of ferrite materials is particularly important because repeated oxidation–reduction cycles can modify their morphology and reduce their hydrogen-production capacity.

Consequently, further research is required to improve ferrite composition, redox kinetics, structural stability, reactor configuration, heat recovery, and gas separation. Development of ferrite materials capable of maintaining high reactivity over many cycles while reducing the required operating temperature could significantly improve the feasibility of this approach [59]. Overall, ferrite-based thermochemical cycles provide a potentially promising route for solar- or heat-driven hydrogen production, although substantial technological development is still necessary before large-scale commercial deployment can be achieved.

Ferrite-based thermochemical systems derive their potential primarily from the reversible redox behavior of iron-containing oxides. During successive reduction and oxidation steps, ferrites can release and subsequently incorporate oxygen, allowing the active material to participate repeatedly in the water-splitting cycle. This regenerative behavior is essential for continuous hydrogen production because the iron-oxide material acts as a recyclable reaction medium rather than being consumed during the overall process.

A further advantage is the abundance and relatively low cost of iron. Compared with thermochemical systems that depend on scarce or expensive materials, iron oxide-based compounds offer the possibility of reducing material-related costs and improving the economic attractiveness of the technology. Their comparatively broad availability could also facilitate large-scale deployment if the associated reactor and process-engineering challenges can be overcome. Similar to other thermochemical pathways, ferrite-based systems can be configured as closed-loop processes in which the redox material is continuously regenerated and reused. Such recycling reduces material consumption and can improve the overall resource efficiency of the system [60].

Despite these favorable characteristics, the technological maturity of thermochemical hydrogen production remains relatively limited. Current deployment is predominantly concentrated in laboratory investigations, pilot plants, and experimental demonstration systems. Commercial-scale installations remain under development, and reliable estimates of globally installed thermochemical hydrogen-production capacity are therefore difficult to establish. The limited number of demonstration projects and the absence of widespread commercial facilities indicate that these technologies currently contribute only a very small fraction of the global hydrogen market.

Hydrogen generated through thermochemical pathways can achieve relatively high purity following appropriate gas separation and purification. Depending on the specific cycle, reactor configuration, and downstream gas-cleaning system, hydrogen purity can commonly exceed 99%, although applications requiring stringent fuel-cell or other high-purity specifications may require additional purification [24]. The achievable product quality is therefore strongly dependent on effective separation of hydrogen from residual steam, oxygen, and other gaseous species.

Overall, high-temperature thermochemical cycles—including sulfur–iodine, Hybrid Sulfur, cerium oxide-based, and ferrite-based systems—offer an alternative route for producing hydrogen using high-temperature heat rather than relying solely on conventional electrical electrolysis. Their principal opportunities include integration with concentrated solar thermal energy, advanced nuclear heat sources, recyclable reaction materials, and high-efficiency thermal-energy management. However, high operating temperatures, material degradation, corrosion, complex reactor configurations, heat-transfer requirements, gas separation, and high initial capital costs remain important barriers to commercialization.

Further advances in materials development, reactor engineering, thermal integration, process intensification, product separation, and long-duration cyclic stability will be essential for moving these technologies beyond the experimental stage. A consolidated assessment of the principal challenges and opportunities associated with high-temperature thermochemical hydrogen-production processes is presented in Table 4.

Continued research and development (R&D) are essential for overcoming the technical and economic barriers associated with high-temperature thermochemical hydrogen production. Current efforts are focused on developing advanced materials with improved thermal stability, corrosion resistance, and long-term redox performance, while also improving reactor configurations to achieve more effective heat and mass transfer. Advances in catalyst and redox-material design, together with improved control of reaction conditions, can enhance conversion efficiency and reduce material degradation during repeated operating cycles.

At the system level, process integration and thermal management remain critical areas of development. Improved heat-recovery strategies can reduce energy losses, while optimized reactor designs can facilitate more uniform temperature distribution and more efficient utilization of high-temperature heat. Integration of thermochemical cycles with concentrated solar thermal systems and advanced nuclear heat sources may further improve their sustainability and enable the direct utilization of high-temperature thermal energy for hydrogen production.

Future progress will therefore depend on coordinated advances in materials science, reactor engineering, heat integration, process optimization, and renewable-energy coupling. Continued technological innovation and demonstration at progressively larger scales will be necessary to establish the reliability, economic feasibility, and long-term durability of these systems. Collectively, these developments could help unlock the potential of high-temperature thermochemical processes as an important pathway for producing low-carbon hydrogen and supporting the transition toward sustainable energy systems.

2.5 Hydrogen Quality Standards and Purification Methods

The availability of multiple hydrogen-production pathways—including water electrolysis, biomass conversion, and thermochemical cycles—creates a need for standardized hydrogen-quality specifications to ensure that the resulting product is suitable for downstream applications. Hydrogen purity is particularly important for fuel-cell systems because even trace quantities of certain contaminants can adversely affect catalyst activity, membrane performance, electrochemical efficiency, and component durability. Consequently, internationally recognized standards have been developed to define acceptable impurity concentrations and establish consistent criteria for hydrogen quality.

In 2012, the International Organization for Standardization (ISO) introduced ISO 14687-2:2012, which established hydrogen-quality requirements for proton exchange membrane fuel-cell (PEMFC) applications. Subsequently, the Society of Automotive Engineers (SAE) published SAE J2719-2015 in 2015, providing additional specifications for hydrogen intended for fuel-cell electric vehicles. These standards were developed to establish consistent limits for contaminants that could negatively influence PEMFC performance and to facilitate the reliable use of hydrogen across different production and distribution systems.

China initially applied GB/T 3634.2-2011, which primarily addressed hydrogen intended for industrial applications. However, this standard did not comprehensively regulate several trace contaminants that are particularly relevant to fuel-cell operation. Recognizing the need for more stringent specifications, China introduced GB/T 37244-2018 toward the end of 2018. This standard was developed with reference to the requirements established in ISO 14687-2:2012 and SAE J2719-2015 and introduced more comprehensive controls on hydrogen purity and impurity concentrations.

The GB/T 37244-2018 specification addresses fourteen major impurity categories that can influence hydrogen quality and fuel-cell performance. These include water (H_2O), total hydrocarbons expressed as methane, oxygen (O_2), helium (He), nitrogen (N_2), argon (Ar), carbon dioxide (CO_2), carbon monoxide (CO), total sulfur compounds expressed as H_2S, formaldehyde (HCHO), formic acid (HCOOH), ammonia (NH_3), total halides expressed as halide ions, and particulate matter. Controlling these substances is particularly important because contaminants such as carbon monoxide, sulfur-containing compounds, ammonia, and hydrocarbons can interact with fuel-cell catalysts or other components and reduce system performance.

Under this classification, hydrogen can be differentiated into pure hydrogen, high-purity hydrogen, and ultra-high-purity hydrogen, with corresponding minimum purity levels of approximately 99.99%, 99.999%, and 99.9999%, respectively. The allowable concentrations of the remaining impurities are correspondingly restricted to maintain the required product quality. Such classification provides a framework for matching hydrogen quality with the requirements of different end-use applications.

The establishment and harmonization of hydrogen-quality standards are therefore essential for the development of a reliable hydrogen economy. Standardized specifications facilitate hydrogen production, purification, transportation, storage, refueling, and end-use, while ensuring that hydrogen supplied from different production pathways satisfies the quality requirements of sensitive applications such as PEM fuel cells. As hydrogen deployment expands, continued refinement and international harmonization of these standards will be important for ensuring interoperability, safety, performance, and consumer confidence across emerging hydrogen supply chains.

Table 4: Principal challenges and prospective opportunities associated with high-temperature thermochemical hydrogen production, encompassing materials, process efficiency, heat integration, scalability, and economic viability.

Aspect	Major challenges	Key opportunities	Technological strategies	Priority actions
Material stability and longevity	Severe corrosion, chemical reactivity, and repeated thermal cycling can degrade reactor and system components	Development of materials capable of maintaining structural and chemical stability under extreme operating conditions	High-temperature alloys, advanced ceramics, protective coatings, and additively manufactured components with tailored properties	Expand materials R&D, conduct long-duration durability testing, and validate advanced materials under realistic operating conditions
High-temperature reactor economics	High fabrication, installation, and maintenance costs associated with reactors operating at elevated temperatures	Cost reduction through optimized reactor architectures, modularization, and scalable manufacturing	Cost-efficient reactor designs, modular reactors, and advanced manufacturing methods including 3D printing	Provide policy incentives, financial support, and demonstration funding to accelerate commercial development
Energy conversion and thermal efficiency	Large thermal requirements and inefficient heat utilization can constrain overall hydrogen-production efficiency	Recovery and reuse of process heat can significantly improve energy utilization	High-performance heat exchangers, waste-heat recovery, thermal storage, and integrated heat-management systems	Support infrastructure development, conduct pilot-scale testing, and promote collaborative R&D on thermal integration
Reaction kinetics and process control	Slow reaction rates and unfavorable kinetics can limit hydrogen production and overall process productivity	Improved reaction rates can increase hydrogen yield and reduce operating requirements	Advanced catalysts, optimized reactor configurations, and precise temperature-management strategies	Invest in catalyst development, optimize reactor operation, and establish collaborative research programs
Renewable-energy integration	Intermittent availability of solar and other renewable energy sources can complicate stable high-temperature operation	Flexible integration with renewable electricity, solar heat, waste heat, and energy-storage systems can improve system flexibility	Smart-grid interfaces, thermal and electrical energy storage, flexible operating strategies, and renewable-heat integration	Strengthen policy support, promote integrated demonstration projects, and develop coordinated renewable-energy and hydrogen infrastructure

Continued advances in proton exchange membrane fuel cell (PEMFC) technology have significantly changed the requirements for hydrogen quality. Improvements such as reduced platinum (Pt) catalyst loading, thinner proton-conducting membranes, increased operating current density, and operation under lower-humidity conditions have enhanced fuel-cell performance and reduced material requirements. However, these developments have also increased the sensitivity of PEMFC systems to certain trace contaminants. Consequently, impurity limits established in earlier hydrogen-quality standards required reassessment to ensure that hydrogen supplied to modern fuel cells would not adversely affect electrochemical performance or long-term durability.

In response to these technological developments, the ISO Technical Committee for Hydrogen Energy (ISO/TC 197) introduced the revised ISO 14687:2019 standard in November 2019. This standard consolidated and updated three previously established hydrogen-fuel-related standards, providing a more comprehensive framework for hydrogen quality across fuel-cell applications. Under ISO 14687:2019, hydrogen intended for PEMFC applications is required to have a minimum purity of approximately 99.97%, while the concentrations of specified contaminants are subject to strict limits. The revised requirements were intended to account for the greater sensitivity of modern PEMFCs resulting from their improved catalyst utilization, thinner membranes, higher current densities, and reduced humidity operation.

The development of ISO 14687:2019 was accompanied by corresponding updates within the automotive industry. In March 2020, the Society of Automotive Engineers (SAE) issued SAE J2719:2020-03, building upon the revised ISO framework and modifying the allowable concentrations of selected impurities, including methane (CH_4), nitrogen (N_2), argon (Ar), and formaldehyde (HCHO). These revisions reflect the continuing evolution of fuel-cell systems and the need to balance stringent hydrogen-quality requirements with the practical characteristics of hydrogen production, purification, and distribution.

It is important to distinguish the stated total impurity limits when comparing different standards and editions, because the overall allowable impurity concentration depends on the specific application and the individual limits assigned to each contaminant. The cited specifications report a minimum hydrogen purity of 99.97%, with the total permissible impurity level expressed as approximately 714.2 ppm in one formulation and 1312 ppm in the later specification. Therefore, hydrogen-quality assessment should rely not only on the nominal hydrogen purity but also on the concentration of individual contaminants that may have disproportionate effects on PEMFC catalysts, membranes, and other components.

The progressive revision of hydrogen-quality standards demonstrates that hydrogen specifications must evolve alongside fuel-cell technology. As PEMFCs continue to operate at higher current densities, lower catalyst loadings, and increasingly demanding conditions, precise control of contaminant concentrations becomes increasingly important. Harmonized and application-specific standards will consequently remain essential for ensuring reliable fuel-cell operation while supporting the development of large-scale hydrogen production and distribution infrastructure.

The permissible concentration of impurities in hydrogen fuel is strictly controlled because their effects are strongly dependent on the materials, architecture, operating conditions, and electrochemical characteristics of PEM fuel cells. Even trace quantities of certain contaminants can reduce cell efficiency, accelerate degradation, or cause irreversible damage to electrocatalytic components. Among the different contaminants, carbon monoxide (CO) is particularly critical because of its strong interaction with platinum-based catalyst surfaces. Consequently, hydrogen supplied to PEMFCs must satisfy stringent impurity limits to ensure stable operation and an adequate service lifetime [60-63].

The effects of individual impurity groups are summarized below:

- Water (H_2O): Although water is an intrinsic component of PEMFC operation, excessive water or contaminated water streams can negatively affect cell performance. Water can transport dissolved ionic contaminants, including Na^+ and K^+, into the membrane and thereby reduce proton conductivity. Excessive water accumulation can also promote corrosion or deterioration of metallic components and contribute to flooding, which restricts effective gas transport within the electrode structure.
- Hydrocarbons (HCs): Many hydrocarbons can adsorb onto electrocatalyst surfaces or accumulate within the catalyst layer, thereby blocking active sites and reducing catalytic activity. Methane (CH_4) is comparatively less reactive toward the fuel-cell catalyst, but elevated methane concentrations dilute the hydrogen feed and consequently reduce the effective hydrogen concentration available for electrochemical oxidation.
- Carbon dioxide (CO_2): CO_2 primarily affects PEMFC operation through dilution of the hydrogen stream, reducing the partial pressure of hydrogen at the anode. Under certain operating conditions, CO_2 can also participate in reverse water–gas shift chemistry, generating CO. The resulting CO can subsequently poison platinum catalyst sites and further reduce fuel-cell performance.
- Carbon monoxide (CO): CO is one of the most detrimental contaminants for PEMFCs. It strongly adsorbs onto platinum active sites, competing with hydrogen for adsorption and substantially reducing the electrochemically active surface area available for hydrogen oxidation. Even relatively small concentrations can therefore cause significant losses in cell voltage and efficiency. Prolonged exposure may contribute to persistent catalyst degradation and reduced fuel-cell lifetime.
- Sulfur-containing compounds: Sulfur species, including sulfides and hydrogen sulfide (H_2S), can strongly interact with platinum catalyst surfaces. Their adsorption blocks active sites required for hydrogen oxidation and can promote the formation of stable platinum–sulfur species. Because the resulting catalyst deactivation can be difficult to reverse, sulfur contamination is considered particularly serious for PEMFC applications.
- Formaldehyde (HCHO) and formic acid (HCOOH): These oxygen-containing organic contaminants can interact with the catalyst and may undergo reactions that generate CO. The resulting CO can then adsorb strongly onto platinum sites, producing an indirect poisoning mechanism and reducing the catalytic activity of the electrode.
- Ammonia (NH_3) and ammonium species: Ammonia can interact with the acidic functional groups of the polymer electrolyte and form ammonium species, potentially decreasing membrane proton conductivity. Adsorption of ammonia-derived species onto catalyst surfaces can additionally block electrochemically active sites and interfere with hydrogen oxidation.
- Helium (He), argon (Ar), and nitrogen (N_2): These relatively inert gases do not normally poison the catalyst directly, but their presence dilutes the hydrogen stream. Increased concentrations therefore lower the hydrogen partial pressure and can reduce the electrochemical driving force and overall cell voltage. Their accumulation can also affect gas transport and diffusion within the electrode structure.
- Halides: Halide contaminants can adsorb onto catalyst surfaces and reduce the number of sites available for electrochemical reactions. Chloride ions, in particular, may interact with components of the membrane and catalyst system, promoting the formation of soluble chloride species and contributing to platinum dissolution. Such processes can accelerate catalyst degradation and negatively affect long-term PEMFC durability.
- Particulate matter: Solid particles can accumulate on catalyst surfaces and physically block active sites, thereby restricting hydrogen access to the electrocatalyst.

Particulates may also obstruct filters and gas-flow pathways, increase pressure losses, and contribute to mechanical or functional damage to cell components. Effective filtration of the hydrogen stream is therefore necessary to prevent particulate contamination.

Overall, the impact of hydrogen impurities extends beyond simple reductions in nominal fuel purity. Different contaminants can act through catalyst poisoning, membrane degradation, gas dilution, reduced proton conductivity, corrosion, active-site blockage, and deterioration of gas transport. These effects can occur individually or synergistically, making rigorous hydrogen purification and quality control essential for maintaining PEMFC efficiency and durability [60-63]. Consequently, hydrogen-production systems must incorporate appropriate purification, drying, filtration, and contaminant-monitoring technologies before the product gas is delivered to sensitive fuel-cell applications.

Hydrogen purification represents a critical stage in the hydrogen production-to-utilization chain, particularly for applications involving fuel-cell vehicles. The establishment of stable, reliable, and economically viable hydrogen supplies depends not only on efficient hydrogen production but also on the ability to consistently deliver hydrogen that satisfies stringent fuel-quality requirements. Consequently, the development of high-efficiency and energy-efficient purification technologies is essential for the expansion of hydrogen infrastructure and the broader commercialization of hydrogen fuel-cell systems.

The performance, efficiency, and durability of a fuel-cell power system are highly dependent on the quality of the hydrogen supplied to it. Hydrogen generated through coal gasification, natural-gas reforming, methanol reforming, coke-oven gas processing, ammonia-related processes, biomass gasification, or water electrolysis is generally referred to as crude hydrogen before downstream purification. Such hydrogen contains varying concentrations of water, carbon oxides, hydrocarbons, sulfur compounds, nitrogen-containing species, and other contaminants depending on the production pathway. Therefore, crude hydrogen generally cannot be supplied directly to PEM fuel-cell vehicles without appropriate purification and quality control.

The composition of crude hydrogen varies substantially with the feedstock and production technology. Representative hydrogen concentrations reported for different sources include approximately 25–35% for coal gasification, 70–75% for natural-gas reforming, 75–80% for methanol reforming, 45–60% for coke-oven gas, 70–80% for methanol purge gas, 60–75% for synthetic-ammonia tail gas, and 25–35% for biomass gasification [63-65]. These substantial differences demonstrate that purification requirements cannot be considered independently of the hydrogen-production route.

In particular, water electrolysis can provide hydrogen of comparatively high purity because the principal products are hydrogen and oxygen. Nevertheless, downstream drying and purification may still be necessary to remove residual water, oxygen, dissolved or entrained species, and other contaminants introduced during processing, compression, or storage. In contrast, hydrogen obtained from carbon-containing feedstocks generally requires more extensive purification because the raw product gas contains numerous chemical species formed during reforming, gasification, or associated conversion reactions.

Therefore, the selection of a hydrogen-purification technology should consider feed-gas composition, required hydrogen purity, contaminant concentration, operating pressure, energy consumption, recovery rate, capital cost, and the intended end use. For fuel-cell applications, purification systems must be capable of meeting stringent impurity limits while minimizing hydrogen losses and additional energy requirements. Technologies such as pressure swing adsorption (PSA), membrane separation, cryogenic separation, adsorption-based purification, and hybrid purification systems can consequently play an important role in converting crude hydrogen into fuel-cell-grade hydrogen.

The development of efficient purification technologies is thus fundamental to establishing a reliable hydrogen supply chain. By combining appropriate purification with hydrogen production, compression, storage, transportation, and quality monitoring, it becomes possible to ensure that hydrogen delivered to fuel-cell vehicles meets the required specifications while improving the overall economic and environmental performance of the hydrogen-energy system.

Hydrogen purification technologies can broadly be divided into physical and chemical methods, with each category encompassing several separation approaches. Physical purification methods include adsorption, low-temperature separation, and membrane separation. Adsorption-based techniques include pressure swing adsorption (PSA), temperature swing adsorption (TSA), and vacuum swing adsorption (VSA). Low-temperature approaches include cryogenic distillation and low-temperature adsorption, whereas membrane-based separation can employ either inorganic or organic membranes. Chemical purification methods primarily include metal-hydride separation and catalytic purification, in which hydrogen selectively reacts with or is transported through a specific material.

The selection of a suitable purification technology depends strongly on the hydrogen-production pathway, composition of the crude hydrogen, required product purity, production scale, operating pressure, and hydrogen supply mode. For centralized, large-scale hydrogen production from coal gasification or natural-gas reforming, particularly when the hydrogen supply exceeds approximately 10 000 Nm^3h^{-1}, pressure swing adsorption (PSA) is widely employed. In these systems, PSA is generally implemented downstream of processes such as water–gas shift conversion, desulfurization, and decarbonization, which reduce the concentration of major contaminants before the final purification stage.

PSA has been extensively developed and industrially demonstrated because of its relatively low operating cost, high reliability, and long service life. The process exploits differences in the adsorption affinities of hydrogen and contaminant gases on porous adsorbent materials. Under elevated pressure, impurities are preferentially adsorbed while hydrogen passes through as the product. Subsequent pressure reduction regenerates the adsorbent, allowing the cycle to be repeated continuously.

Despite these advantages, conventional PSA systems may exhibit limitations when hydrogen is required to meet the particularly stringent specifications associated with fuel-cell vehicles. Depending on the composition of the feed gas and the operating conditions, hydrogen recovery can decrease because a portion of the hydrogen remains in the impurity-rich off-gas during regeneration. Consequently, improving hydrogen recovery while simultaneously achieving ultra-low contaminant concentrations remains an important research objective.

Cryogenic distillation represents another potential purification approach, particularly for large-scale hydrogen processing. The technique separates components based on differences in their boiling points and can be advantageous when processing large gas streams. However, conventional cryogenic separation may produce hydrogen with a purity of approximately 85–99%, depending on the process configuration and feed composition, which may be insufficient for direct use in demanding fuel-cell applications [66]. Additional purification or polishing steps may therefore be necessary to achieve fuel-cell-grade hydrogen.

Overall, no single purification technology is universally optimal. PSA is well suited to large centralized hydrogen-production facilities, while membranes, adsorption processes, cryogenic separation, metal-hydride systems, and catalytic purification can provide complementary or alternative solutions. Increasingly, hybrid purification systems that combine two or more technologies are being investigated to simultaneously improve hydrogen purity, recovery, energy efficiency, and economic performance. Such integrated approaches are particularly important for producing high-quality hydrogen that satisfies stringent PEMFC requirements while minimizing hydrogen losses throughout the purification process.

The appropriate hydrogen purification technology depends strongly on the scale of hydrogen production, supply configuration, feed-gas composition, and type and concentration of impurities. Consequently, purification systems suitable for large centralized plants may not be practical for decentralized or vehicle-refueling applications.

For centralized by-product hydrogen production with a hydrogen supply capacity of approximately 1000–10 000 $Nm^3 h^{-1}$, more versatile purification processes are required to improve hydrogen recovery while effectively removing impurities. The optimal configuration depends on the composition of the crude hydrogen stream. In these systems, purification technologies may be combined or adapted to selectively remove specific contaminants while minimizing hydrogen losses. This is particularly important for by-product hydrogen because its composition can vary considerably depending on the industrial process from which the hydrogen is recovered.

For small-scale, on-site, or distributed hydrogen production, generally involving hydrogen supplies of $\leq$1000 $Nm^3 h^{-1}$, conventional PSA becomes less attractive. Although PSA is well established for large-scale applications, its deployment at smaller scales can be constrained by its relatively large footprint, operational complexity, limited flexibility, and lower adaptability to variable feed compositions. These limitations become particularly relevant when purification is integrated directly with hydrogen-refueling infrastructure or distributed production facilities.

Under these conditions, alternative technologies such as low-temperature adsorption, metal-hydride separation, and metal-membrane separation can provide more appropriate solutions. The selection among these technologies should be based on the nature and concentration of the impurities present in the hydrogen stream.

Low-temperature adsorption is particularly attractive because it can simultaneously remove multiple contaminants, including sulfur-containing compounds, formaldehyde (HCHO), and formic acid (HCOOH). This capability can be advantageous when several trace impurities must be removed to satisfy stringent fuel-cell hydrogen specifications. However, maintaining low operating temperatures requires additional energy for cooling and thermal management. Consequently, low-temperature adsorption is more suitable for specific small-scale applications where an appropriate cold source is readily available, rather than as a universally applicable purification technology [67, 68].

Metal hydride separation offers another promising approach because certain metals and alloys can selectively absorb hydrogen and subsequently release it under controlled pressure or temperature conditions. This selectivity can enable high-purity hydrogen production while potentially combining purification with hydrogen storage. Similarly, metal membranes can exploit the preferential permeability of hydrogen through metallic materials to separate hydrogen from other gases. These approaches may offer compact configurations that are particularly attractive for decentralized hydrogen production and refueling systems.

Thus, the transition toward distributed hydrogen production requires purification technologies that are not simply scaled-down versions of conventional large-scale systems. Instead, future purification systems should emphasize compactness, flexibility, high hydrogen recovery, low energy consumption, rapid response, and compatibility with variable feed compositions. Integrating adsorption, membrane, metal-hydride, and catalytic processes into hybrid configurations could provide an effective pathway toward reliable and economical purification for decentralized hydrogen-energy applications.

Metal-hydride separation and palladium (Pd) membrane separation have demonstrated considerable potential for purifying hydrogen streams containing relatively high concentrations of inert gases. These technologies exploit the selective interaction or transport of hydrogen through the separation medium, enabling the production of high-purity hydrogen from complex gas mixtures. Such characteristics make them attractive for applications where conventional adsorption-based purification may be less effective.

However, both approaches present an important limitation during the hydrogen recovery stage. Interaction between the regenerated or purified material and the impurity-containing feed gas can reduce the effective separation performance. In metal-hydride systems, repeated absorption and desorption can also influence material stability and hydrogen-storage capacity, while Pd membranes may experience performance degradation depending on operating conditions and the composition of the feed stream. Consequently, improving material durability, hydrogen recovery, and resistance to impurity-induced degradation remains an important research objective.

Several advanced membrane technologies are therefore receiving increasing scientific attention. Carbon molecular sieve membranes (CMSMs) can provide highly selective molecular separation because of their finely controlled microporous structures. Ionic-liquid membranes offer tunable physicochemical properties and can potentially provide high selectivity toward hydrogen or other target species. Electrochemical hydrogen-pump membranes represent another promising approach, in which an applied electrical potential drives hydrogen selectively through a proton-conducting membrane, simultaneously enabling purification and, in some configurations, compression.

Despite their promising laboratory-scale performance, the transition of these emerging technologies to industrial-scale applications remains challenging. Major barriers include membrane fabrication and scale-up, long-term stability, resistance to contaminants, mechanical durability, manufacturing cost, and maintaining high hydrogen flux and selectivity under realistic operating conditions. Further research is therefore needed to translate advances in membrane materials into reliable commercial purification systems.

Overall, hydrogen purification is an indispensable component of the hydrogen-production chain, regardless of whether hydrogen originates from water electrolysis, natural-gas reforming, coal or biomass gasification, by-product recovery, or thermochemical processes. Appropriate purification is required to remove water, carbon oxides, sulfur compounds, hydrocarbons, nitrogen-containing species, particulates, and other contaminants and to obtain hydrogen that meets the quality specifications of the intended application [69-71]. The selection of purification technology must consequently consider the feed composition, production scale, required purity, hydrogen recovery, energy consumption, capital cost, and end-use requirements. A comparative summary of the principal purification technologies, together with their major advantages, limitations, and application areas, is presented in Table 5.

2.6 Hydrogen Delivery and Transport Infrastructure

As hydrogen production expands to support the global transition toward low-carbon energy systems, the development of efficient, reliable, and economically viable hydrogen transportation infrastructure will become increasingly important. Hydrogen must be transported from production facilities to industrial users, energy-storage facilities, refueling stations, and other points of consumption. Among the available transportation options, the repurposing of existing natural-gas pipeline networks has attracted considerable attention as a potentially cost-effective pathway for accelerating hydrogen deployment [72].

A major advantage of this approach is the ability to utilize existing infrastructure. Extensive natural-gas pipeline networks are already distributed across many regions and include pipelines, compressor stations, valves, metering equipment, and associated distribution facilities. Reusing suitable portions of this infrastructure could reduce the need for entirely new hydrogen-specific pipeline systems and thereby lower both capital expenditure and construction requirements.

Repurposing existing pipelines could also shorten the time required to establish a hydrogen transportation network. Constructing new pipelines requires substantial investment, land acquisition, permitting, environmental assessment, and lengthy construction periods. In contrast, adapting existing natural-gas infrastructure, where technically feasible, could allow hydrogen distribution to develop more rapidly. This would be particularly valuable during the early stages of hydrogen-market development, when transportation infrastructure may otherwise represent a major bottleneck between hydrogen production and end users.

The economic benefits extend beyond pipeline construction. Existing rights-of-way, maintenance systems, monitoring infrastructure, and operational expertise could potentially be retained, reducing the overall cost of establishing a hydrogen supply chain. Repurposing infrastructure may therefore provide a transitional strategy that supports the gradual expansion of hydrogen demand while dedicated hydrogen infrastructure is developed where required.

However, existing natural-gas pipelines cannot automatically be assumed to be suitable for pure hydrogen service. Hydrogen has different physical and chemical characteristics from natural gas, including its lower molecular weight, high diffusivity, wide flammability range, and potential to cause hydrogen embrittlement in susceptible materials. Pipeline steels, welds, seals, valves, compressors, and other components must therefore be assessed for compatibility with hydrogen. Operating pressure, hydrogen concentration, pipeline age, material composition, and previous service history are important factors in determining whether a particular pipeline can safely be repurposed.

Consequently, pipeline conversion may involve material assessment, component replacement, leak detection, compressor modification, pressure management, and enhanced safety monitoring. In some cases, blending hydrogen with natural gas may provide an intermediate pathway, whereas dedicated hydrogen transport may ultimately be required for applications demanding high-purity hydrogen.

Overall, repurposing natural-gas pipelines represents a potentially valuable bridge toward a mature hydrogen transportation network. Its principal advantages are the utilization of existing infrastructure, reduced capital requirements, faster deployment, and the possibility of accelerating hydrogen-market development. Nevertheless, detailed technical, economic, regulatory, and safety assessments are necessary to determine which existing pipelines can be safely and efficiently converted for hydrogen service.

The repurposing of natural-gas pipeline networks provides an additional strategic advantage through their extensive geographic coverage. Existing pipelines often connect major production centers with industrial, commercial, and residential demand centers across both urban and rural regions. Utilizing this established network could facilitate the distribution of hydrogen over large distances without requiring the immediate construction of an entirely new transportation system. This approach may be particularly valuable in regions where new pipeline construction is constrained by high capital costs, difficult terrain, land-use limitations, or lengthy permitting processes [73].

Beyond geographic accessibility, the technical feasibility of hydrogen transport through existing natural-gas pipelines has become an important area of research. Although hydrogen and methane can both be transported as gases, their physical and chemical properties differ substantially. Hydrogen has a much lower molecular mass and smaller molecular size, higher diffusivity, and different interactions with pipeline materials. These characteristics must be carefully considered when evaluating the suitability of existing natural-gas infrastructure for hydrogen service.

One important concern is hydrogen leakage. Because hydrogen molecules are considerably smaller and more mobile than methane molecules, they can migrate through very small imperfections, joints, seals, valves, and fittings. Consequently, existing pipeline components may require inspection, replacement, or modification to minimize leakage and maintain system integrity. Improved leak-detection technologies and monitoring systems may also be required when hydrogen concentrations increase.

Another major concern is hydrogen-induced embrittlement. Hydrogen can enter susceptible metallic materials and interact with their microstructure, potentially reducing ductility and fracture resistance. This issue is particularly important for high-strength steels, welds, and other components exposed to elevated hydrogen pressures. Repeated pressure cycling can further influence material behavior and fatigue performance. Therefore, the suitability of a natural-gas pipeline for hydrogen service depends on factors such as material composition, manufacturing history, operating pressure, temperature, weld characteristics, and pipeline age [74].

In addition, hydrogen can influence the performance requirements of compressors, valves, seals, regulators, and metering equipment. Components originally designed for natural gas may not necessarily provide equivalent performance when exposed to hydrogen. Repurposing projects therefore require a system-wide assessment rather than evaluating the pipeline itself in isolation.

Overall, existing natural-gas pipelines offer considerable potential for accelerating hydrogen deployment because of their geographic reach and established infrastructure base. However, successful conversion requires comprehensive evaluation of leakage, material compatibility, embrittlement, fatigue, component performance, and operational safety. Addressing these challenges through material screening, infrastructure upgrades, advanced monitoring, and appropriate regulatory standards will be essential for enabling safe and economically viable hydrogen transportation through repurposed pipeline networks.

Despite the technical challenges associated with hydrogen transport, research indicates that a substantial portion of existing natural-gas pipeline infrastructure may be suitable for hydrogen service following appropriate modifications and safety assessments. Pipeline adaptation can involve the application of hydrogen-compatible materials and protective coatings to reduce susceptibility to embrittlement, together with improvements in seals, valves, compressors, and other components exposed to hydrogen. Enhanced inspection, monitoring, and maintenance practices are also important for identifying leakage and maintaining pipeline integrity over long operating periods.

An alternative transitional strategy is the blending of hydrogen with natural gas. Introducing hydrogen into existing natural-gas networks at controlled concentrations can enable the gradual integration of hydrogen without requiring immediate conversion of the entire infrastructure to dedicated hydrogen service. Hydrogen blending at concentrations of up to approximately 20% by volume has been investigated and demonstrated in various projects, although the technically and economically appropriate blending limit depends on pipeline materials, appliances, end-use requirements, pressure conditions, and applicable regulations. This approach can therefore serve as an intermediate pathway while dedicated hydrogen infrastructure is progressively developed.

Pilot projects and field demonstrations are playing an important role in determining the practical feasibility of hydrogen transportation through existing pipeline systems. These projects provide valuable information concerning hydrogen leakage, material degradation, embrittlement, compressor performance, blending behavior, gas quality, and operational safety. The resulting experience can support the identification of best practices and contribute to the development of technical standards, safety protocols, and regulatory frameworks governing hydrogen pipeline transportation.

The economic argument for pipeline repurposing is equally significant. Constructing an entirely new hydrogen pipeline network requires substantial capital expenditure for pipeline materials, rights-of-way, compressor stations, valves, metering systems, and associated infrastructure. Where existing natural-gas pipelines can be safely adapted, much of the established infrastructure and associated rights-of-way can potentially be retained. This can substantially reduce the initial investment and shorten infrastructure-development timelines.

Lower transportation-infrastructure costs could improve the competitiveness of hydrogen relative to alternative energy carriers, particularly during the early stages of hydrogen-market development when demand and dedicated infrastructure remain limited. Repurposing therefore offers a potentially important bridge between today's natural-gas infrastructure and a future hydrogen-oriented energy network [75].

Nevertheless, economic benefits must be evaluated alongside conversion costs, pipeline integrity assessments, component replacement, leakage control, hydrogen losses, maintenance requirements, and regulatory compliance. The most appropriate strategy may therefore involve a combination of hydrogen blending, selective pipeline conversion, and construction of dedicated hydrogen pipelines, depending on regional demand, existing infrastructure characteristics, and the required hydrogen purity and delivery conditions.

The integration of hydrogen into existing natural-gas pipeline networks can provide important economic and systemic benefits beyond simply reducing infrastructure-development costs. By utilizing existing pipeline capacity, hydrogen can be transported through an established energy-delivery network, potentially improving the overall utilization and economic efficiency of the existing infrastructure. This approach may also create new revenue opportunities for pipeline operators while providing a gradual pathway for reducing the carbon intensity of conventional natural-gas systems [76].

Hydrogen integration can also support broader objectives related to energy security and supply diversification. Transporting domestically produced hydrogen through existing pipeline networks can reduce reliance on imported fossil fuels and improve the resilience of national energy systems. At the same time, the development of domestic hydrogen production, transportation, storage, and utilization infrastructure can stimulate local industrial development and employment opportunities across the hydrogen value chain. Regions with abundant renewable-energy resources could consequently use hydrogen production to strengthen local economies while supplying energy to distant demand centers.

From an environmental perspective, the potential benefits of hydrogen pipeline transportation are closely associated with the carbon intensity of hydrogen production. Hydrogen produced using renewable electricity through water electrolysis, or through appropriately managed renewable-feedstock pathways, can provide a low-carbon energy carrier. When existing natural-gas pipelines are repurposed rather than constructing entirely new transportation infrastructure, additional environmental impacts associated with new pipeline construction—including material production, land disturbance, construction activities, and associated energy consumption—can potentially be reduced [77].

The environmental advantage is therefore twofold: low-carbon hydrogen can reduce emissions associated with energy use, while infrastructure repurposing can reduce the additional environmental burden associated with building new transportation networks. However, the overall climate benefit depends on factors such as the hydrogen production pathway, leakage rates, pipeline modifications, energy consumption during compression, and the extent to which natural gas is displaced by hydrogen.

Consequently, repurposing natural-gas pipelines can be viewed as a potentially important component of a gradual transition toward hydrogen-based energy systems. Its combination of infrastructure utilization, economic diversification, energy-security benefits, and potential environmental advantages makes it attractive during the development of the hydrogen economy. Nevertheless, these benefits must be balanced against technical compatibility, safety, hydrogen leakage, material degradation, and the need for appropriate regulatory frameworks to ensure that pipeline conversion delivers genuine long-term decarbonization benefits.

In addition to its potential economic and environmental advantages, the integration of hydrogen into existing natural-gas pipeline networks is increasingly supported by evolving energy policies, regulatory frameworks, and decarbonization strategies. Governments and regulatory authorities are developing policies to facilitate hydrogen deployment, including incentives for infrastructure adaptation, technical and safety standards, hydrogen-blending guidelines, and long-term targets for low-carbon hydrogen production and utilization.

The development of appropriate regulatory and safety frameworks is particularly important because hydrogen differs from natural gas in its physical and chemical behavior. Standards governing pipeline materials, operating pressures, hydrogen concentrations, leakage detection, equipment compatibility, and emergency response can provide the technical basis for safe hydrogen transportation. Financial incentives and supportive policies can further reduce the economic barriers associated with assessing and modifying existing pipeline infrastructure.

The compatibility of hydrogen pipeline integration with broader energy-transition and decarbonization objectives provides an additional justification for this approach. As governments and industries pursue net-zero-emission targets, existing natural-gas infrastructure represents a potentially valuable asset that can be progressively adapted rather than immediately abandoned. Hydrogen blending and selective pipeline conversion can therefore provide transitional pathways while dedicated hydrogen infrastructure is developed where necessary.

From a strategic perspective, repurposing suitable natural-gas pipelines offers a pragmatic and potentially cost-effective mechanism for accelerating hydrogen infrastructure deployment. It can connect emerging hydrogen-production centers with existing energy-demand regions while reducing the time and investment required for constructing entirely new networks. However, successful implementation will depend on coordinated policies that address technical compatibility, safety, hydrogen quality, leakage control, economic incentives, and long-term infrastructure planning.

Ultimately, the effectiveness of this pathway will depend on ensuring that policy support, technological development, infrastructure investment, and environmental objectives evolve together. Such coordination can enable existing pipeline networks to contribute to the gradual development of a resilient hydrogen economy while supporting the broader transition toward low-carbon and eventually net-zero energy systems.

Table 5. Key challenges and potential opportunities in the standardization, purification, and quality management of green hydrogen for reliable and application-specific utilization.

Hydrogen production pathway	Principal challenges	Potential opportunities	Technological approaches	Priority actions
Water electrolysis	High electricity demand and gradual degradation of membranes can affect operating efficiency and service life	Higher conversion efficiency and extended membrane durability can reduce operating costs and improve long-term performance	Advanced ion-exchange membranes, molecular-sieve technologies, PSA-based purification, and durable membrane materials	Increase R&D on low-energy processes, improve membrane lifetime, and accelerate development of robust electrolyzer and purification systems
Biomass gasification	Complex impurity profiles and environmental concerns associated with biomass residues complicate hydrogen purification and waste management	Production of cleaner syngas while converting sustainable biomass residues into useful energy carriers	Advanced filtration, gas washing, adsorption/absorption systems, and improved residue-management technologies	Develop high-performance gas-cleaning systems, promote sustainable residue utilization, and establish effective waste-management practices
High-temperature thermochemical processes	Extreme operating temperatures, material corrosion, and management of process by-products can reduce system durability and efficiency	Improved recovery and utilization of secondary products can enhance resource efficiency while reducing corrosion-related losses	High-temperature-resistant membranes, corrosion-resistant materials, permeation-based separation, and advanced by-product recovery systems	Invest in durable materials and membrane development, improve by-product management, and optimize integrated recovery processes

Although the repurposing of natural-gas pipelines presents a promising pathway for expanding hydrogen transportation infrastructure, further research and technological development are required to establish its long-term safety, reliability, and economic feasibility. One important research area concerns the long-term interaction between hydrogen and pipeline materials. Extended exposure to hydrogen, particularly under high pressure and repeated pressure cycling, may influence material strength, fatigue resistance, weld integrity, and susceptibility to hydrogen embrittlement. Comprehensive long-duration studies are therefore needed to determine the service-life limitations of different pipeline materials and components under hydrogen-rich operating conditions.

Another important area is the development of advanced hydrogen-leak detection and monitoring technologies. Because hydrogen has high diffusivity and can escape through very small defects or imperfect seals, conventional natural-gas monitoring systems may not always provide adequate detection capability. Future systems should incorporate highly sensitive sensors, continuous monitoring, automated data analysis, and potentially distributed sensing technologies capable of rapidly identifying and locating hydrogen leaks. Such developments will be essential for improving operational safety and minimizing hydrogen losses.

Further research is also required to optimize hydrogen blending strategies. The appropriate hydrogen concentration in a natural-gas network depends on pipeline materials, pressure, end-use equipment, gas composition, appliance compatibility, and regulatory requirements. Research should therefore examine the effects of different hydrogen concentrations on pipeline integrity, compressors, valves, meters, storage systems, and downstream users. Developing standardized methodologies for determining safe and economically optimal blending limits will support more effective integration of hydrogen into existing gas networks.

Addressing these challenges will require strong collaboration among industry, academic institutions, research organizations, and government agencies. Industry can provide operational experience and infrastructure data, academia can contribute materials research and advanced monitoring technologies, and government agencies can establish appropriate safety standards, certification procedures, and regulatory frameworks. Coordinated efforts can help translate laboratory findings into practical engineering solutions.

Finally, continued investment in pilot projects and large-scale demonstration facilities will be essential. Real-world demonstrations provide opportunities to evaluate hydrogen transport under representative operating conditions, identify unexpected degradation mechanisms, validate monitoring technologies, and establish reliable operating procedures. The knowledge generated from these projects can strengthen technical standards and increase stakeholder confidence in the safety and reliability of hydrogen pipeline transportation.

Overall, the successful transition from natural-gas to hydrogen-compatible pipeline infrastructure will depend on a combination of materials innovation, advanced monitoring, optimized blending, rigorous safety assessment, supportive regulation, and large-scale demonstration. Continued progress in these areas can help establish repurposed pipelines as a reliable transitional component of a future low-carbon hydrogen transportation network.

The potential use of existing natural-gas pipelines for hydrogen transportation represents a compelling opportunity to accelerate the development of a hydrogen-based energy system. By leveraging established infrastructure, the approach can reduce the time and capital required to develop new transportation networks while facilitating connections between hydrogen-production centers and geographically dispersed end users [72-74, 76, 78].

However, realizing this potential requires simultaneous progress in pipeline adaptation, materials compatibility, leak detection, hydrogen blending, safety management, and regulatory development. Existing infrastructure must be evaluated on a case-by-case basis to determine its suitability for hydrogen service, while appropriate modifications and monitoring systems should be implemented where necessary. Regulatory frameworks must also evolve to establish clear requirements for pipeline conversion, operating conditions, hydrogen quality, blending limits, inspection, maintenance, and emergency response.

Public engagement and stakeholder acceptance represent another important dimension of hydrogen infrastructure development. Transparent communication regarding hydrogen safety, environmental benefits, infrastructure modifications, and emergency-management procedures can help build public confidence and facilitate the deployment of hydrogen transportation projects. Early engagement among communities, infrastructure operators, regulators, and other stakeholders can also help identify concerns and improve project planning.

The opportunities associated with pipeline repurposing extend beyond transportation itself. A growing hydrogen infrastructure can stimulate technological innovation, industrial development, investment, and employment across hydrogen production, purification, compression, storage, transportation, monitoring, and end-use sectors. It can also contribute to energy diversification by enabling greater utilization of domestically produced hydrogen and reducing dependence on conventional fossil-fuel supply chains.

From an environmental perspective, the use of low-carbon or renewable hydrogen within existing infrastructure can support the decarbonization of energy systems, provided that hydrogen production has a sufficiently low lifecycle carbon intensity and infrastructure-related hydrogen leakage is effectively controlled. Thus, pipeline repurposing can serve as a transitional mechanism linking existing natural-gas infrastructure with emerging low-carbon energy systems.

Overall, the future development of hydrogen pipeline transportation will require coordinated action across industry, government, academia, regulators, and society. Combining infrastructure adaptation with technological innovation, robust regulatory standards, public engagement, and continued demonstration projects can help overcome existing barriers. If these challenges are effectively addressed, repurposed natural-gas pipelines could become an important component of large-scale hydrogen distribution and contribute significantly to the broader objectives of energy security, economic development, sustainability, and decarbonization. A consolidated assessment of the major challenges and opportunities is presented in Table 6.

3. Maturity Assessment of Hydrogen Production Technologies

The transition toward sustainable hydrogen production has resulted in the development of a wide range of technologies with different levels of technological maturity. These technologies vary considerably in terms of technical development, demonstration, commercial deployment, scalability, and economic viability. Therefore, assessing their Technology Readiness Level (TRL) provides an effective framework for evaluating the maturity of each technology and determining its proximity to large-scale commercial application.

TRL assessment enables researchers, industry stakeholders, investors, and policymakers to distinguish between laboratory-scale concepts, pilot and demonstration technologies, and commercially established processes.

Technologies with high TRLs have generally undergone extensive testing under representative or operational conditions and are closer to widespread deployment, whereas technologies at lower TRLs require additional research, validation, optimization, and demonstration before commercialization.

For sustainable hydrogen production, technologies such as alkaline and PEM water electrolysis have achieved comparatively advanced levels of maturity, while emerging pathways—including high-temperature thermochemical cycles, advanced biomass-based processes, and novel electrolysis configurations—remain at varying stages of development. The TRL framework therefore provides valuable insight into the technological gaps that must be addressed, including efficiency improvement, durability, cost reduction, scalability, material development, and system integration.

A clear understanding of TRLs is particularly important for strategic investment and technology selection. Mature technologies can be prioritized for near-term deployment, whereas less-developed technologies can receive targeted research and development support to overcome technical and economic barriers. Figure 7 summarizes the TRLs of the major sustainable hydrogen-production technologies discussed in this review, illustrating their relative technological maturity and potential for future commercialization.

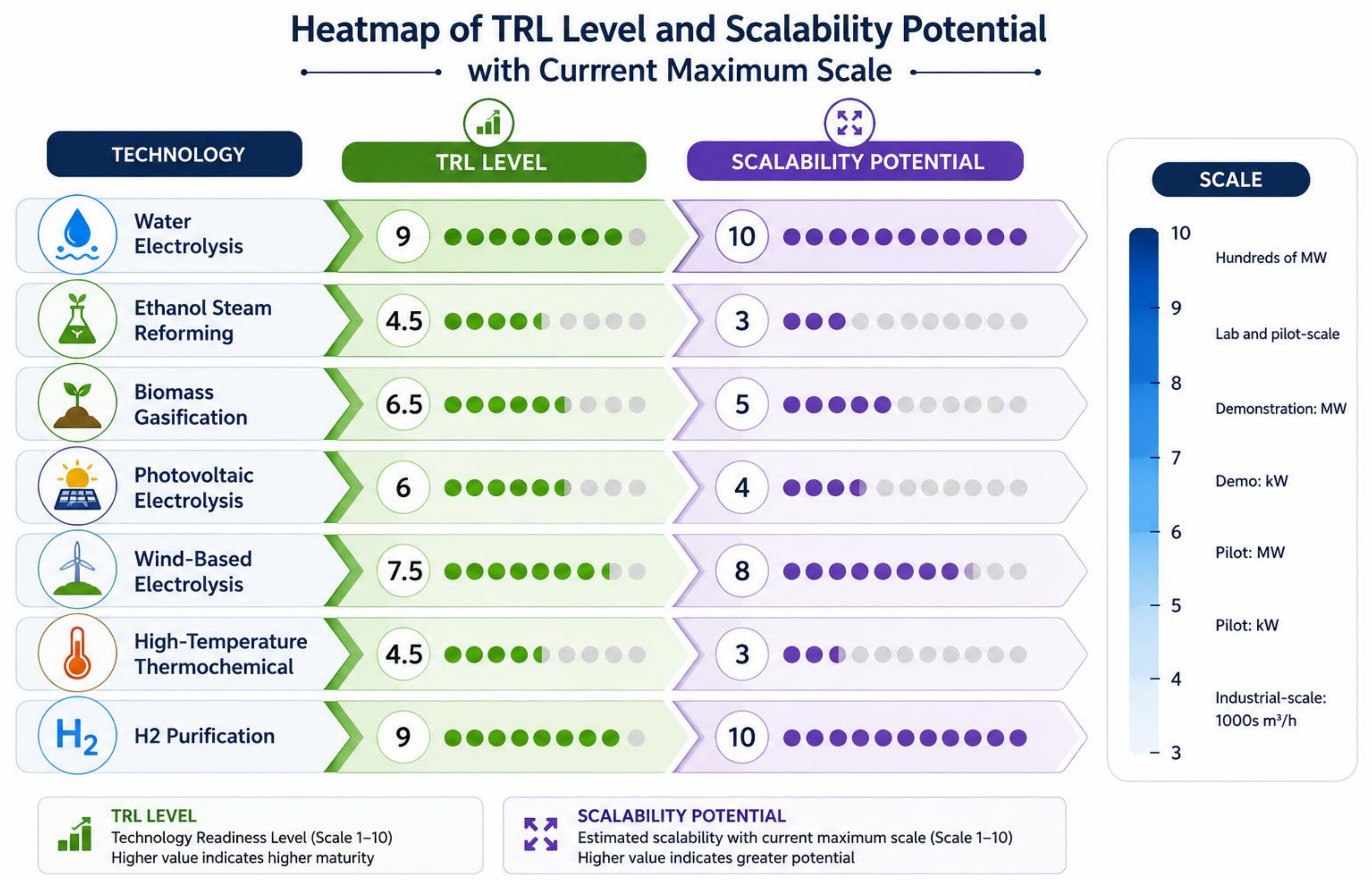

Figure 7: Comparative assessment of the Technology Readiness Levels (TRLs) of major hydrogen production technologies, highlighting their respective stages of technological development and commercial deployment.

Among the sustainable hydrogen-production pathways, water electrolysis technologies exhibit comparatively high technological maturity. Alkaline electrolysis and Proton Exchange Membrane (PEM) electrolysis have been extensively demonstrated and are increasingly being deployed at commercial scale. Solid oxide electrolysis (SOE) also offers considerable potential because of its high efficiency and ability to utilize high-temperature heat, although further improvements in durability, thermal management, and long-term operational stability are required for broader large-scale deployment.

Wind-based electrolysis is approaching commercial-scale implementation, supported by the increasing deployment of large wind farms and the integration of electrolyzers with variable renewable electricity. Photovoltaic (PV) electrolysis has also progressed beyond laboratory research into pilot and demonstration projects, although further improvements in system integration, intermittency management, energy storage, and cost are required to achieve widespread commercial deployment.

Biomass gasification represents a comparatively advanced thermochemical pathway, with pilot and demonstration projects providing valuable information regarding feedstock handling, syngas quality, tar removal, process integration, and hydrogen purification. Nevertheless, variability in biomass feedstocks, process complexity, and economic considerations continue to influence its large-scale commercialization.

In contrast, ethanol steam reforming remains at an earlier stage of development. Although the use of renewable ethanol offers opportunities for utilizing established bioethanol infrastructure and renewable feedstocks, further research is required to improve catalyst stability, minimize carbon deposition, optimize operating conditions, and establish economically viable large-scale supply chains.

High-temperature thermochemical cycles, including sulfur–iodine, hybrid sulfur, cerium oxide-based, and ferrite-based cycles, generally remain at relatively early stages of technological development. Their potential for highly efficient hydrogen production using concentrated solar energy or nuclear heat is significant, but challenges involving high operating temperatures, corrosion, materials durability, reactor design, heat integration, and system complexity must be overcome before commercial deployment.

Hydrogen purification technologies, particularly Pressure Swing Adsorption (PSA) and established membrane-separation processes, are comparatively mature and already widely applied in industrial gas processing. However, emerging technologies such as advanced membranes, electrochemical hydrogen pumps, and novel adsorption materials continue to be investigated to improve hydrogen recovery, energy efficiency, and purification performance.

Overall, the TRL landscape demonstrates that sustainable hydrogen production is characterized by a diverse technological portfolio: mature electrolysis and purification technologies can support near-term deployment, while biomass-based, renewable-integrated, and high-temperature thermochemical technologies offer additional pathways requiring varying degrees of demonstration and optimization. This differentiation is important for directing research funding, infrastructure investment, commercialization strategies, and policy support toward technologies according to their respective maturity and remaining development requirements.

Table 6: Major technical, economic, safety, infrastructural, and regulatory challenges, together with emerging opportunities for the efficient and sustainable transportation of green hydrogen.

Strategic dimension	Key challenges	Potential opportunities	Technological / strategic solutions	Priority actions
Pipeline conversion and infrastructure	Material incompatibility, hydrogen-induced embrittlement, leakage risks, and potentially high modification costs	Reusing existing natural-gas networks can substantially reduce the cost and time required for hydrogen infrastructure development	Hydrogen-compatible materials, protective coatings, reinforced pipelines, advanced leak-detection and monitoring systems	Increase materials R&D, strengthen industry–academia collaboration, provide infrastructure funding incentives, and promote public–private investment
Regulation and standardization	Fragmented policies, regulatory uncertainty, and the absence of harmonized technical requirements may discourage investment	Consistent standards and regulatory certainty can stimulate market development and facilitate international hydrogen trade	Harmonized technical standards, certification systems, safety regulations, and standardized pipeline-operation protocols	Establish clear regulatory frameworks, coordinate national and international standards, and strengthen policy alignment
Geopolitical factors and public acceptance	International tensions, supply-chain vulnerabilities, safety concerns, and limited public understanding may delay deployment	International cooperation and improved public confidence can support a coordinated global hydrogen economy	Enhanced safety technologies, transparent monitoring systems, international cooperation mechanisms, and public-information initiatives	Strengthen diplomatic cooperation, conduct public-awareness campaigns, and improve communication regarding hydrogen safety and benefits
Environmental sustainability	Conventional hydrogen production can have a substantial carbon footprint, while infrastructure development may create additional environmental burdens	Renewable hydrogen provides an important pathway for decarbonization and integration of clean energy into multiple sectors	Renewable-powered electrolysis, renewable-energy integration, and low-carbon hydrogen infrastructure	Expand renewable-energy capacity, increase investment in green hydrogen, and establish policies that accelerate the transition away from carbon-intensive hydrogen
Economic development and employment	High initial investment requirements, skills shortages, and the need for new industrial capabilities can constrain sector growth	Expansion of the hydrogen economy can generate employment, stimulate industrial development, and create new markets across multiple sectors	Hydrogen infrastructure, advanced materials and safety technologies, digital monitoring and control systems, and innovative hydrogen applications	Invest in workforce training and education, support technology development, promote cross-sector collaboration, and encourage hydrogen-related industrial innovation

Overall, the technology-readiness assessment demonstrates that hydrogen-production pathways are progressing at different rates of technological maturity. While established technologies such as alkaline and PEM electrolysis and conventional hydrogen-purification systems are approaching or have reached commercial deployment, other pathways—including biomass-based processes, renewable-integrated electrolysis, ethanol reforming, and high-temperature thermochemical cycles—continue to advance through laboratory research, pilot testing, and demonstration projects. This diversity reflects both the complexity of sustainable hydrogen production and the broad range of technological options available for different energy and industrial applications.

The development and deployment of hydrogen-production technologies will be critical to achieving a sustainable and low-carbon energy future. However, the challenges and opportunities associated with each technology are strongly influenced by its Technology Readiness Level (TRL). Mature technologies primarily require improvements in cost competitiveness, scalability, durability, infrastructure integration, and operational efficiency. In contrast, technologies at lower TRLs require fundamental research, material development, process optimization, pilot-scale validation, and demonstration under realistic operating conditions.

A strategic approach should therefore recognize that no single hydrogen-production technology is likely to satisfy all future energy requirements. Instead, complementary technologies can be developed according to regional renewable resources, available feedstocks, energy demand, infrastructure, and end-use requirements. Continued innovation across the

TRL spectrum can accelerate the transition from laboratory concepts to commercially viable systems.

In this context, research and development, industrial demonstration, supportive policy frameworks, infrastructure investment, and collaboration among academia, industry, and governments are essential for reducing technological and economic barriers. Advancing technologies through successive TRLs will ultimately strengthen their reliability, reduce costs, improve environmental performance, and enable broader integration of hydrogen into sustainable energy systems. Figure 7 therefore provides a useful framework for understanding the current maturity of hydrogen technologies while also highlighting their future development potential and remaining technological gaps.

4. Policy Frameworks for Advancing Green Hydrogen Technologies

Policies developed by governments, international organizations, and regulatory institutions play a central role in accelerating the development and deployment of green hydrogen technologies. Because green hydrogen continues to face challenges related to production costs, infrastructure requirements, technological maturity, market uncertainty, and regulatory complexity, policy support is essential for creating favorable conditions for research, commercialization, and large-scale adoption.

Policy interventions generally encompass several complementary mechanisms, including research and development funding, capital subsidies, tax incentives, production incentives, public procurement, financial guarantees, infrastructure support, and regulatory frameworks. These measures can help reduce investment risks, encourage technological innovation, and improve the competitiveness of green hydrogen relative to conventional hydrogen produced from fossil fuels.

The policy landscape also varies according to the Technology Readiness Level (TRL) of individual production pathways. Mature technologies such as alkaline and PEM electrolysis can benefit from deployment incentives, infrastructure development, renewable-electricity integration, and mechanisms that reduce production costs. Emerging technologies—including solid oxide electrolysis, biomass gasification, ethanol reforming, and high-temperature thermochemical cycles—often require greater emphasis on fundamental research, pilot projects, demonstration programs, and technology-specific innovation funding.

At the international level, hydrogen policies are increasingly connected with broader objectives related to climate mitigation, energy security, industrial decarbonization, renewable-energy expansion, and sustainable economic development. National hydrogen strategies commonly establish production targets, infrastructure objectives, financial-support mechanisms, and regulatory requirements intended to create predictable investment environments. International cooperation is particularly important for developing common definitions, certification systems, hydrogen-quality standards, carbon-intensity criteria, and cross-border transportation frameworks.

An important policy objective is also the development of integrated hydrogen value chains. Support for production alone may be insufficient if hydrogen storage, transportation, purification, distribution, and end-use infrastructure remain underdeveloped. Coordinated policies can therefore encourage investment across the entire hydrogen ecosystem, including electrolyzers, renewable-energy generation, pipelines, storage facilities, refueling stations, industrial applications, and fuel-cell technologies.

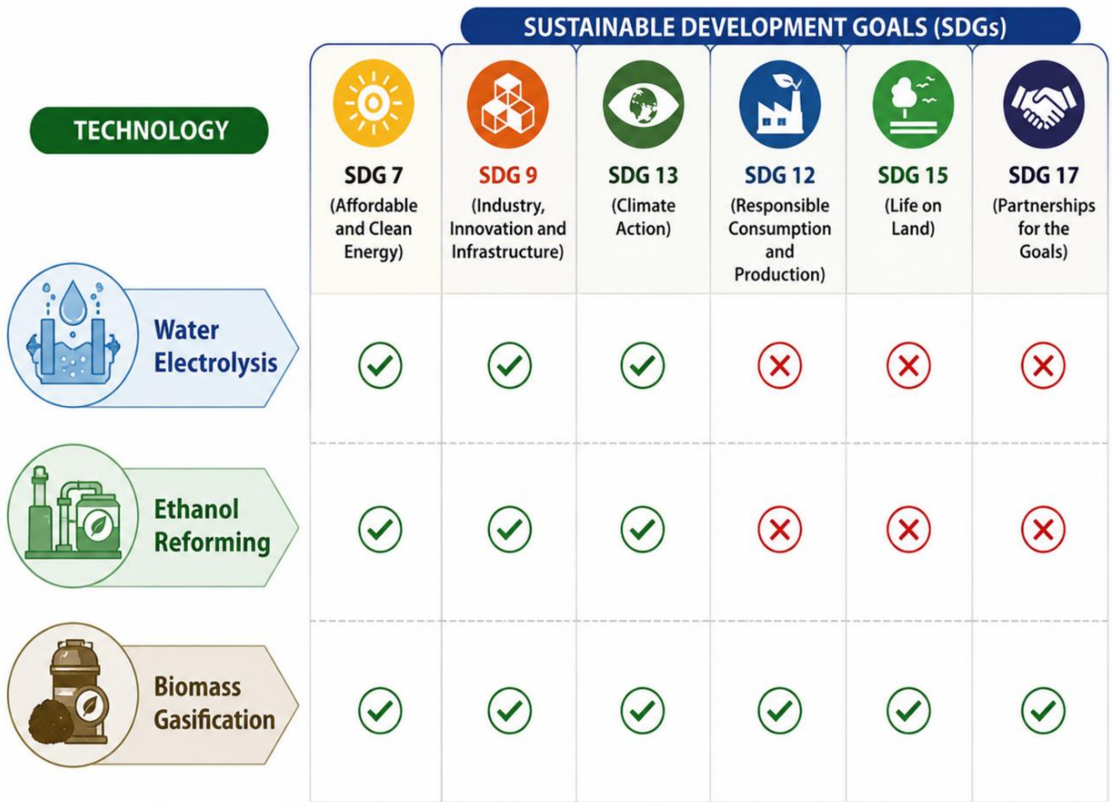

Figure 8: Overview of hydrogen production technologies and their contributions to achieving the Sustainable Development Goals (SDGs), highlighting their potential environmental, economic, and societal impacts.

Furthermore, policy frameworks can help address the economic and social dimensions of the hydrogen transition. The expansion of green hydrogen industries can create employment in manufacturing, engineering, construction, operation, maintenance, logistics, and research. Regions with abundant solar, wind, or biomass resources may also benefit from new industrial activity and improved energy security. However, policymakers must ensure that hydrogen development remains environmentally sustainable and does not create excessive pressure on water resources, land, electricity systems, or local communities.

Overall, effective green-hydrogen policy requires a coordinated combination of technological, economic, environmental, and regulatory measures. Policies should evolve as technologies progress through different TRLs, gradually shifting from research support toward commercialization and market-based mechanisms. Such an approach can accelerate innovation, reduce investment risks, stimulate private-sector participation, and establish the infrastructure required for large-scale hydrogen deployment.

The following section therefore examines key policies and initiatives implemented by different regions and institutions, with particular emphasis on their support for green-hydrogen production technologies, the challenges and opportunities they create, and their contribution toward achieving the 2030 Sustainable Development Agenda [79].

4.1 European Union (EU)

The European Union (EU) has positioned green hydrogen as an important component of its long-term decarbonization strategy. Through the European Green Deal, the European Commission established the objective of achieving climate neutrality across Europe by 2050, with hydrogen identified as an important option for reducing emissions in sectors that are difficult to electrify directly, particularly heavy industry, chemicals, refining, and parts of the transport sector.

The EU Hydrogen Strategy places strong emphasis on renewable hydrogen produced through water electrolysis. Its initial deployment objectives included reaching at least 6 GW of renewable-hydrogen electrolyzer capacity by 2024 and 40 GW by 2030. These targets have helped stimulate investment in electrolyzer manufacturing, renewable-energy integration, hydrogen infrastructure, and industrial demonstration projects [80].

Among electrolysis technologies, alkaline electrolysis (AEL) and proton exchange membrane (PEM) electrolysis have received considerable attention because of their relatively high technological maturity and potential for large-scale deployment. AEL benefits from extensive industrial experience and comparatively mature components, while PEM electrolysis offers rapid response to fluctuations in renewable electricity, making it particularly suitable for integration with variable solar and wind generation.

The EU policy framework also supports the development of less mature electrolysis technologies, including solid oxide electrolysis (SOE). SOE has attracted interest because its high operating temperature can improve energy efficiency and enable integration with industrial waste heat or other high-temperature heat sources. However, issues involving material durability, thermal cycling, system complexity, and long-term stability remain important development challenges.

Financial mechanisms such as the EU Innovation Fund provide additional support for innovative low-carbon technologies and demonstration projects. Such funding can help bridge the gap between laboratory-scale innovation and commercial deployment by reducing the financial risks associated with first-of-a-kind projects. In the hydrogen sector, this type of support is particularly valuable for technologies that have significant long-term potential but have not yet achieved the same level of commercial maturity as conventional alkaline or PEM systems.

Overall, the European approach combines long-term climate objectives, electrolyzer deployment targets, technology-specific innovation support, and industrial decarbonization policies. This integrated framework can accelerate the development of both mature and emerging hydrogen technologies while strengthening Europe's renewable-energy and low-carbon industrial sectors. At the same time, achieving the intended scale of deployment requires continued progress in reducing electrolyzer costs, expanding renewable electricity generation, developing hydrogen storage and transportation infrastructure, and establishing stable market and regulatory conditions.

4.2 United States

In the United States, the U.S. Department of Energy (DOE), particularly through its Hydrogen and Fuel Cell Technologies Office (HFTO), has established a broad research and development framework to accelerate hydrogen technologies. The DOE's hydrogen programs support advances across the hydrogen value chain, with particular emphasis on reducing production costs, improving efficiency, increasing durability, and enabling large-scale deployment of renewable and clean hydrogen.

A major objective of the DOE Hydrogen Program has been to reduce the cost of hydrogen produced from renewable resources, with particular attention to Proton Exchange Membrane (PEM) and alkaline electrolysis (AEL). These technologies are considered important pathways because of their technological maturity and compatibility with renewable electricity. PEM electrolyzers offer rapid dynamic response and are therefore well suited to variable renewable generation, whereas AEL benefits from established industrial experience and scalability.

The Infrastructure Investment and Jobs Act (IIJA) has provided substantial federal support for clean-hydrogen development, including the establishment of regional clean hydrogen hubs. These hubs are intended to connect hydrogen production with transportation, storage, industrial applications, and other end uses, thereby supporting integrated regional hydrogen ecosystems. Such an approach can reduce infrastructure fragmentation and demonstrate the feasibility of hydrogen deployment at larger scales [81].

U.S. policy support also extends beyond mature electrolysis technologies. The DOE has supported research into high-temperature steam electrolysis (HTSE) based on solid oxide electrolysis (SOE), which can potentially achieve high efficiency by combining electricity with externally supplied thermal energy. Integration with industrial waste heat or other high-temperature heat sources may further improve system performance.

In addition, the United States is investigating next-generation hydrogen-production approaches, including photocatalytic water splitting and other advanced technologies that could ultimately reduce electricity requirements or simplify hydrogen production. Although these technologies remain less mature than conventional electrolysis, continued research funding can help address fundamental challenges involving efficiency, materials stability, scalability, and system integration.

Overall, the U.S. policy approach combines cost-reduction targets, federal R&D, infrastructure investment, regional hydrogen hubs, and support for emerging technologies. This combination is intended to accelerate the transition from laboratory and pilot-scale technologies toward commercially competitive hydrogen production. Continued progress will depend on reducing electrolyzer and renewable-electricity costs, developing supporting infrastructure, improving technology durability, and creating sufficiently strong markets for clean hydrogen across industrial, transportation, and energy applications.

4.3 Japan

Japan has adopted a long-term strategy to establish a “hydrogen society”, positioning hydrogen as an important energy carrier for power generation, transportation, and industrial applications. Through its Basic Hydrogen Strategy, Japan has established targets and policy measures covering hydrogen production, storage, transportation, infrastructure development, and end-use applications. Particular emphasis has been placed on Proton Exchange Membrane (PEM) and alkaline electrolysis (AEL) because of their technological maturity and potential compatibility with renewable-energy systems.

Japan has also established the Green Innovation Fund, which provides substantial long-term financial support for technologies contributing to decarbonization. The fund has allocated approximately $19 billion over ten years to support innovative technologies, including advanced hydrogen-production systems. Within this framework, research into solid oxide electrolysis (SOE) and photocatalytic water splitting is intended to improve hydrogen-production efficiency, reduce costs, and accelerate the commercialization of emerging technologies.

Japan's policy approach therefore combines near-term deployment of relatively mature electrolysis technologies with long-term investment in advanced production pathways. This strategy is particularly relevant to Japan because of its limited domestic fossil-fuel resources and the need to develop diversified and secure low-carbon energy supplies.

4.4 China

China has likewise identified hydrogen as an important component of its long-term energy-transition strategy. The Hydrogen Industry Development Plan (2021–2035) emphasizes the expansion of hydrogen-production capacity, development of supporting infrastructure, and establishment of an integrated hydrogen industry. The strategy includes ambitious objectives for hydrogen mobility, including a target of approximately one million hydrogen fuel-cell vehicles by 2030, accompanied by the expansion of hydrogen-refueling infrastructure [82].

China's hydrogen-development policies place considerable emphasis on the deployment of alkaline electrolysis (AEL) and PEM electrolysis, reflecting their relatively high technological maturity. AEL is particularly attractive for large-scale applications because of its established industrial experience and scalability, while PEM technology offers rapid response and strong compatibility with variable renewable electricity.

At the same time, China is investing in next-generation hydrogen-production technologies, including solid oxide electrolysis and novel biological pathways. Research into biological water splitting using microorganisms such as algae and bacteria represents an emerging area that could provide alternative approaches to renewable hydrogen production, although these technologies remain at comparatively low TRLs and require substantial further research before large-scale commercialization.

China's successive Five-Year Plans have increasingly incorporated hydrogen within broader objectives for renewable-energy development, industrial decarbonization, and the country's goal of achieving carbon neutrality by 2060. Government-supported R&D programs, pilot projects, infrastructure development, and industrial demonstrations are intended to accelerate the transition from technological development toward commercial deployment.

4.5 Australia

Australia has identified hydrogen as a strategic component of its future clean-energy economy through its National Hydrogen Strategy, with the objective of establishing the country as a major producer and exporter of low-emission hydrogen. Australia's extensive solar and wind resources provide favorable conditions for large-scale renewable hydrogen production, while its existing energy and export infrastructure creates opportunities for integration into international hydrogen supply chains.

The strategy emphasizes the development of hydrogen hubs, where production, storage, transportation, and end-use facilities can be geographically integrated. Such hubs can reduce infrastructure costs, improve resource utilization, and facilitate the development of regional hydrogen industries. The strategy also supports the development of appropriate regulatory and certification frameworks, which are important for ensuring hydrogen quality, environmental performance, safety, and international market compatibility. International cooperation is another important component, particularly for developing hydrogen-export markets and harmonizing standards.

Australia's policy framework places considerable emphasis on alkaline electrolysis (AEL) and Proton Exchange Membrane (PEM) electrolysis. These technologies are well suited to Australia's renewable-energy resources, although their large-scale deployment requires continued reductions in electrolyzer costs, improvements in efficiency and durability, and effective integration with variable solar and wind electricity.

The Australian Renewable Energy Agency (ARENA) plays an important role in supporting this transition by providing grants and financial assistance for renewable-energy and green-hydrogen projects. Such funding helps reduce the financial risks associated with early-stage projects, supports technology demonstration, and encourages private-sector investment. A major objective is to reduce hydrogen-production costs while increasing the scale and efficiency of production systems.

Australia is also investigating innovative hydrogen-production pathways. Solar-to-hydrogen systems, particularly photovoltaic-driven electrolysis, can directly couple abundant solar resources with hydrogen production. This approach offers significant potential for low-carbon hydrogen production but requires solutions for solar intermittency, electrolyzer utilization, energy storage, and system integration.

In addition, research into biomass gasification provides an alternative pathway for utilizing Australia's biomass and agricultural residues. Although biomass-based hydrogen production is less mature than conventional electrolysis, it could provide opportunities for converting renewable biological resources and organic wastes into hydrogen while potentially contributing to circular-economy objectives.

Overall, Australia's approach combines large-scale renewable-resource development, hydrogen hubs, financial incentives, technology demonstration, regulatory development, and international cooperation. By supporting both mature electrolysis technologies and emerging production pathways, the Australian strategy aims to establish a competitive domestic hydrogen industry while positioning the country as a significant participant in the emerging global hydrogen market.

4.6 International organizations

At the international level, organizations such as the International Energy Agency (IEA) and the Hydrogen Council play an important role in coordinating research, disseminating technical knowledge, and supporting the development of policies that can accelerate the global hydrogen economy.

The IEA Hydrogen Technology Collaboration Programme (TCP) promotes international cooperation in hydrogen-related research, development, demonstration, and deployment. Through collaboration among participating countries and research institutions, the program supports the assessment and advancement of a broad range of hydrogen technologies, including alkaline electrolysis (AEL), Proton Exchange Membrane (PEM) electrolysis, solid oxide electrolysis (SOE), and emerging approaches such as photocatalytic and biological water splitting. Such international collaboration is particularly valuable for sharing technical knowledge, identifying technological barriers, and avoiding duplication of research efforts.

The IEA also provides technology assessments, market analysis, and policy recommendations that can assist governments in evaluating hydrogen-production pathways and designing appropriate deployment strategies. These assessments can help policymakers understand differences in technological maturity, production costs, efficiency, infrastructure requirements, and environmental performance, thereby supporting more informed decisions regarding hydrogen investment and policy development.

The Hydrogen Council represents another important international initiative, bringing together major companies from the energy, transport, industrial, and related sectors to promote the development and adoption of hydrogen technologies. The organization advocates for increased investment, supportive policy frameworks, infrastructure development, and international cooperation to accelerate the transition toward a sustainable hydrogen economy [83].

A key contribution of such international initiatives is the promotion of cross-border collaboration and policy coordination. Hydrogen markets are inherently international because production resources, infrastructure, industrial demand, and potential export markets are often located in different regions. Cooperation can therefore facilitate the development of common standards, certification methodologies, safety requirements, and international supply chains.

Overall, international organizations complement national hydrogen strategies by providing technical knowledge, policy guidance, research collaboration, investment advocacy, and mechanisms for international coordination. Their activities can help accelerate the transition of emerging technologies from research and demonstration toward commercial deployment while supporting the broader objectives of decarbonization, energy security, and sustainable economic development.

4.7 Principal Policy Instruments

4.7.1 Financial Support and Economic Incentives

Governments play a crucial role in accelerating green hydrogen deployment by providing financial incentives, grants, subsidies, and tax credits that reduce capital and operating costs and improve project bankability. Such mechanisms are particularly important during the early stages of market development, when green hydrogen remains less cost-competitive than conventional fossil-based hydrogen.

Financial support can facilitate the commercialization of alkaline electrolysis (AEL), Proton Exchange Membrane (PEM) electrolysis, and solid oxide electrolysis (SOE) by reducing investment risks and encouraging large-scale deployment. Incentives can also stimulate private-sector participation and support the development of associated renewable-energy, storage, transportation, and hydrogen-utilization infrastructure.

4.7.2 Regulatory and Governance Measures

The establishment of clear, consistent, and supportive regulatory frameworks is essential for creating an enabling environment for hydrogen development. Appropriate regulations can simplify permitting procedures, establish safety requirements, define hydrogen-quality specifications, and provide clear rules for the construction and operation of hydrogen-production and transportation infrastructure.

Such frameworks are particularly important for large-scale electrolysis facilities integrated with renewable-energy systems, where issues such as electricity sourcing, water consumption, land use, grid connection, hydrogen storage, pipeline transportation, and environmental compliance must be addressed. Regulatory certainty can reduce project-development delays and provide investors with greater confidence in long-term hydrogen markets.

4.7.3 Research, Innovation, and Technology Development Support

Continued research and development (R&D) is essential for improving the efficiency, durability, scalability, and cost-effectiveness of green hydrogen technologies. Public research funding can support improvements in established technologies such as AEL and PEM electrolysis while simultaneously advancing emerging technologies with potentially greater long-term performance.

Priority research areas include SOE, advanced catalysts and membranes, photocatalytic water splitting, biological hydrogen production, renewable-energy integration, hydrogen storage, and system optimization. R&D support is particularly important for technologies at lower Technology Readiness Levels (TRLs), where technical uncertainties and high development costs can discourage private investment.

4.7.4 Public–Private Collaborative Initiatives

Public–private partnerships (PPPs) provide an effective mechanism for combining government resources and policy support with private-sector expertise, technological capabilities, and investment. These partnerships can distribute financial and technological risks while accelerating the transition of hydrogen technologies from laboratory research to pilot, demonstration, and commercial-scale deployment.

PPPs are particularly valuable for large demonstration projects, where substantial capital investment and long-term operational experience are required. Collaboration among governments, technology developers, energy companies, research institutions, and infrastructure operators can also facilitate knowledge sharing and the development of common technical standards.

Collectively, these policy instruments address several of the principal barriers to green hydrogen deployment, including high production costs, limited infrastructure, technological uncertainty, financing constraints, and insufficient market demand. A coordinated policy portfolio can simultaneously support mature technologies such as AEL and PEM electrolysis and accelerate the development of emerging pathways such as SOE, photocatalytic water splitting, biological hydrogen production, and biomass-based technologies.

Importantly, policy support should evolve with technological maturity. Early-stage technologies require greater emphasis on R&D and demonstration funding, whereas mature technologies benefit increasingly from market-based incentives, infrastructure investment, and regulatory certainty. Such a phased approach can improve the efficient allocation of public resources while accelerating commercialization.

Ultimately, the combined use of financial incentives, supportive regulations, R&D programs, and public–private partnerships can create the conditions necessary for a competitive hydrogen economy. These measures not only support technological innovation and infrastructure development but also contribute to broader 2030 Agenda objectives, including clean energy deployment, industrial decarbonization, sustainable economic growth, job creation, and the transition toward resilient low-carbon energy systems.

5. Green Hydrogen and Power-to-Gas: Advances and Research Progress

Power-to-Gas (PtG) is an emerging energy-conversion pathway that transforms electrical energy—particularly surplus electricity from renewable sources—into hydrogen or synthetic natural gas (SNG). The process generally involves water electrolysis to produce hydrogen, followed, when SNG is required, by a methanation step in which hydrogen reacts with carbon dioxide to form methane. PtG therefore provides a mechanism for converting intermittent renewable electricity into storable chemical energy, helping address the mismatch between renewable-energy generation and energy demand.

The technology can contribute to grid flexibility, renewable-energy integration, long-duration energy storage, and sector coupling. During periods of high solar or wind generation, surplus electricity can be directed to electrolyzers rather than curtailed. The resulting hydrogen can subsequently be stored and used in fuel cells, industrial processes, transportation, or power generation. Alternatively, hydrogen can be converted into SNG, which can potentially utilize existing gas-storage and distribution infrastructure. In this way, PtG can establish a connection between the electricity, gas, transport, and industrial sectors.

Over the past decade, research institutions including ETH Zurich, RWTH Aachen University, Carnegie Mellon University (CMU), and the University of Salamanca (USAL) have contributed to the development and optimization of PtG technologies. Their research has addressed electrolysis performance, renewable-energy integration, methanation, system optimization, techno-economic feasibility, and grid applications [77].

ETH Zurich has contributed significantly to PtG research, particularly in the integration of electrolysis with variable renewable-energy sources. Research has examined the operational behavior of electrolyzers under fluctuating electricity supply, with the objective of optimizing operating strategies and maximizing hydrogen-production efficiency. Such work is particularly relevant because renewable electricity generation varies with weather conditions and can result in rapid changes in available electrical power.

Research at ETH Zurich has also investigated the potential for PtG systems to provide ancillary grid services. Electrolyzers can potentially adjust their electricity consumption in response to grid conditions, allowing PtG facilities to function as flexible loads. This capability can improve system flexibility while simultaneously increasing the utilization of renewable electricity [84].

RWTH Aachen University has made important contributions to PtG, particularly in the field of hydrogen methanation. A major research focus involves the development and optimization of catalysts for the Sabatier reaction, in which hydrogen reacts with carbon dioxide to produce methane and water:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Improving catalyst activity, selectivity, durability, and resistance to deactivation is important for achieving efficient methanation and reducing operating costs.

Research at RWTH Aachen has also included techno-economic assessment and system-level analysis of PtG technologies. These studies examine factors such as electrolyzer and methanation costs, renewable-electricity availability, system efficiency, operating strategies, infrastructure requirements, and potential revenues from energy storage and grid-balancing services. Such assessments are essential for determining the conditions under which PtG can become economically competitive for large-scale energy storage [75].

Overall, PtG provides a promising approach for integrating renewable electricity with chemical-energy storage and existing energy infrastructure. Hydrogen-based PtG can directly support decarbonization, while the conversion of hydrogen into SNG provides an additional pathway for utilizing renewable electricity in applications traditionally dependent on gaseous fossil fuels.

However, the overall feasibility of PtG depends on several factors, including electrolyzer efficiency, methanation efficiency, renewable-electricity prices, carbon-dioxide availability, equipment costs, hydrogen storage requirements, and system operating flexibility. Continued research into advanced electrolyzers, catalysts, control strategies, and integrated system designs will therefore be important for improving the efficiency and economic performance of PtG systems.

Thus, PtG can be regarded as an important sector-coupling technology capable of linking renewable electricity production with hydrogen, synthetic fuels, gas infrastructure, and industrial energy demand. Its continued development may contribute significantly to grid stability, renewable-energy utilization, long-duration energy storage, and the broader transition toward a low-carbon energy system.

Carnegie Mellon University (CMU) has contributed to the development of Power-to-Gas (PtG) technology through system modeling, simulation, and optimization. Its research has focused on evaluating the optimal design and operating conditions of PtG systems, particularly when integrated with existing natural-gas infrastructure. Such integration provides a potential pathway for utilizing hydrogen-enriched natural gas in industrial, commercial, and residential applications, while reducing the need for entirely new gas-distribution infrastructure.

CMU's research has also considered the life-cycle environmental performance of PtG systems. Life-cycle assessment (LCA) provides a comprehensive means of evaluating environmental impacts across different stages of the technology, including electricity generation, hydrogen production, methanation, infrastructure, operation, and eventual utilization. These assessments are important for determining whether PtG systems provide genuine environmental benefits under different energy and operating scenarios [85].

The University of Salamanca (USAL) has investigated PtG within the broader framework of smart grids and renewable-energy integration. Its research has included the development of control strategies and algorithms for dynamically managing PtG systems in response to changes in electricity generation and demand. Effective control is particularly important when PtG facilities are coupled with intermittent renewable sources such as solar and wind, as the available electrical input can vary significantly over time.

USAL has additionally examined the socio-economic dimensions of PtG deployment, including market readiness, economic feasibility, policy requirements, and the conditions necessary for large-scale implementation. These considerations are essential because the successful deployment of PtG depends not only on technological performance but also on supportive regulations, suitable market structures, infrastructure availability, and investment conditions [86, 87].

Collectively, research conducted by ETH Zurich, RWTH Aachen University, Carnegie Mellon University, and the University of Salamanca, together with contributions from other research institutions, has advanced the development of PtG from individual technological components toward integrated energy-system applications. The research covers complementary aspects including:

- Electrolysis and renewable-energy integration for efficient hydrogen production.
- Methanation and catalyst development for synthetic natural-gas production.
- System modeling and optimization to identify suitable configurations and operating strategies.
- Smart-grid integration and dynamic control to manage fluctuating renewable electricity.
- Techno-economic assessment to evaluate scalability and commercial feasibility.
- Life-cycle assessment to quantify environmental performance and sustainability.
- Infrastructure integration to explore the use of existing natural-gas networks.
- Policy and socio-economic analysis to identify barriers to market deployment.

Despite this progress, several challenges remain, particularly energy-conversion losses, high capital costs, catalyst durability, electrolyzer degradation, infrastructure compatibility, and the need for favorable electricity and hydrogen-market conditions. Continued interdisciplinary research will therefore be necessary to improve system efficiency, reduce costs, and demonstrate PtG at increasingly larger scales.

Overall, PtG represents a promising sector-coupling and energy-storage pathway that can convert surplus renewable electricity into hydrogen or synthetic methane. Continued advances in electrolysis, methanation, control systems, infrastructure integration, and policy design could strengthen its role in improving renewable-energy utilization and supporting a flexible, resilient, and low-carbon energy system.

6. Future Pathways for Scaling Green Hydrogen Production

Within the framework of the United Nations 2030 Agenda, circular economy principles, and Industry 4.0, the development of green hydrogen extends beyond technological advancement and requires consideration of geopolitical, economic, environmental, and socioindustrial factors. The integration of green hydrogen into a sustainable energy system is therefore dependent on addressing a broad range of barriers, including high investment requirements, infrastructure limitations, regulatory uncertainty, resource availability, and the unequal geographical distribution of renewable-energy resources and critical raw materials 88].

Looking ahead, green hydrogen has the potential to become an important component of international energy trade and the global transition toward low-carbon energy systems [89]. Achieving this potential will require continued policy development, commercialization of existing technologies, and the introduction of new and more competitive production pathways. Large-scale infrastructure deployment will also require strong cooperation among governments, industries, research institutions, and international organizations. Harmonized regulations, common technical standards, certification systems, and cross-border agreements will be particularly important for establishing reliable international hydrogen markets.

Although economies of scale are expected to reduce the cost of hydrogen production as deployment expands, substantial capital and operating expenditures remain important barriers. Consequently, technological development should focus on improving electrolyzer efficiency, catalyst performance, system durability, renewable-electricity utilization, and process integration, while minimizing energy losses throughout the hydrogen value chain. Increasing efficiency is essential not only for reducing production costs but also for maximizing the environmental benefits of renewable hydrogen.

Another important consideration is the development of a resilient and secure supply chain for critical hydrogen-production components, including electrolyzers, membranes, catalysts, and associated power-electronic systems. Concentration of raw-material extraction and processing in a limited number of geographical regions can create supply-chain vulnerabilities and expose hydrogen projects to price fluctuations, trade restrictions, and geopolitical risks. Diversification of suppliers, recycling of critical materials, development of alternative materials, and establishment of regional manufacturing capabilities can therefore strengthen the long-term resilience of the hydrogen sector.

The integration of carbon capture, utilization, and related carbon-management technologies with hydrogen production can further contribute to circular-economy objectives. Captured CO_2 can be used as a feedstock for the production of synthetic fuels, chemicals, and other value-added products, creating pathways for carbon utilization rather than treating CO_2 solely as a waste stream.

When renewable hydrogen is combined with captured CO_2, for example, it can serve as a key reactant for producing synthetic hydrocarbons and other chemical products. Such integration can promote resource efficiency, industrial symbiosis, and carbon circularity, particularly when the carbon originates from unavoidable industrial or biogenic sources. However, the environmental benefits depend strongly on the origin of the CO_2, the energy required for capture and conversion, and the overall life-cycle emissions of the integrated system.

Advances in hydrogen storage technologies are equally important for the development of a flexible hydrogen economy. Conventional compressed-gas and liquid-hydrogen systems can be complemented by emerging approaches based on advanced materials, metal hydrides, chemical hydrogen carriers, and liquid organic hydrogen carriers (LOHCs). These technologies aim to increase storage density, improve safety, reduce energy requirements, and facilitate long-distance transportation.

The principles of Industry 4.0 can further enhance hydrogen production and distribution through digitalization, automation, artificial intelligence, advanced sensors, digital twins, predictive maintenance, and real-time process optimization. These technologies can enable operators to dynamically match hydrogen production with renewable-energy availability, identify equipment degradation at an early stage, optimize energy consumption, and improve the reliability of large-scale hydrogen systems.

The development of green hydrogen is closely connected with several Sustainable Development Goals (SDGs). In particular:

- SDG 7 – Affordable and Clean Energy: Green hydrogen can facilitate the integration of renewable electricity and provide a storable energy carrier.
- SDG 9 – Industry, Innovation and Infrastructure: Hydrogen technologies can stimulate technological innovation, industrial development, and new energy infrastructure.
- SDG 12 – Responsible Consumption and Production: Circular approaches involving material recycling, carbon utilization, and efficient resource management can improve resource efficiency.
- SDG 13 – Climate Action: Renewable hydrogen can support the decarbonization of difficult-to-electrify sectors such as heavy industry, chemicals, shipping, and long-distance transport.

Overall, the successful development of a global green hydrogen economy will require more than technological improvements alone. Coordinated progress in policy, infrastructure, financing, supply-chain resilience, digitalization, storage, circular-economy practices, and international cooperation will be essential. By combining these elements, green hydrogen can evolve from an emerging energy technology into a significant component of a secure, circular, digitally enabled, and decarbonized global energy system.

Moreover, green hydrogen has the potential to become a significant internationally traded energy commodity, particularly for countries with abundant solar, wind, and other renewable-energy resources. Countries with favorable renewable-energy conditions can use these resources to produce hydrogen for domestic consumption as well as export. The development of hydrogen export industries can stimulate economic growth, industrial investment, employment, and technological development, while strengthening international cooperation around clean-energy systems. In this context, green hydrogen directly supports SDG 17 (Partnerships for the Goals) by encouraging collaboration among countries, industries, financial institutions, and research organizations.

The emergence of international hydrogen trade may also contribute to the diversification and security of global energy supplies. Countries with limited renewable-energy potential could import hydrogen or hydrogen-derived products from resource-rich regions, creating new energy-trade relationships while reducing dependence on conventional fossil fuels. However, establishing such markets will require substantial investments in hydrogen production, storage, transportation, conversion facilities, ports, and associated infrastructure, as well as internationally recognized certification and sustainability criteria.

Within the broader global energy transition, green hydrogen can therefore be regarded as a strategic intersection of technological innovation, energy security, geopolitics, and environmental sustainability. Its development presents significant opportunities for decarbonizing sectors that are difficult to electrify directly, including heavy industry, chemical production, long-distance transportation, shipping, and potentially aviation through hydrogen-derived fuels. At the same time, challenges associated with large-scale infrastructure, energy efficiency, production costs, water availability, storage, transportation, and supply-chain security must be addressed before green hydrogen can achieve widespread deployment [81].

The transition toward a hydrogen-based energy system will consequently depend on the convergence of strategic investment, international collaboration, technological innovation, and forward-looking public policies. Governments can establish supportive regulatory and financial frameworks, industries can accelerate commercialization and infrastructure development, and research institutions can advance more efficient and cost-effective technologies.

Ultimately, the integration of green hydrogen into the global energy mix could contribute to the development of resilient, interconnected, and low-carbon energy systems. Its potential extends beyond replacing fossil-fuel-based hydrogen: green hydrogen can facilitate renewable-energy integration, enable sector coupling, support international clean-energy trade, stimulate industrial development, and contribute to multiple Sustainable Development Goals. Realizing this potential will require coordinated action across national and international levels, ensuring that the expansion of hydrogen infrastructure and markets remains economically viable, environmentally sustainable, and socially inclusive. Such an approach can position green hydrogen as an important component of the 2030 Agenda and the long-term transition toward a sustainable global energy system.

7. Contributions of Hydrogen Production to the Sustainable Development Goals (SDGs)

Green hydrogen production plays a significant role in advancing the Sustainable Development Goals (SDGs) established under the United Nations 2030 Agenda for Sustainable Development. The development of diverse hydrogen-production pathways—including water electrolysis, ethanol steam reforming, biomass gasification, high-temperature thermochemical processes, and hydrogen purification and quality-standard technologies—can contribute to the transition toward cleaner energy systems, sustainable industrial development, and greenhouse-gas emission reduction.

These technologies support the SDGs through several interconnected pathways. Water electrolysis, particularly when powered by renewable electricity, enables the production of low-carbon hydrogen while facilitating the integration of variable renewable-energy sources. Ethanol steam reforming and biomass gasification can utilize renewable or bio-derived feedstocks, potentially supporting resource efficiency and reducing dependence on conventional fossil-based hydrogen. Meanwhile, high-temperature thermochemical cycles provide alternative pathways for hydrogen production using heat from renewable or other low-carbon sources.

The establishment of appropriate hydrogen-quality standards and purification technologies is also essential for the reliable utilization of hydrogen in fuel cells, industrial processes, transportation, and energy systems. High-purity hydrogen improves system performance, protects sensitive equipment, and enables the safe integration of hydrogen into emerging energy applications.

Collectively, these technological pathways contribute particularly to SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). They can also support SDG 12 (Responsible Consumption and Production) through improved resource utilization, process integration, recycling, and circular-economy approaches, while the development of international hydrogen supply chains and technology partnerships can contribute to SDG 17 (Partnerships for the Goals).

The relationship between the major hydrogen-production pathways and their contributions to sustainable development can therefore be summarized in Table 2, highlighting how technological innovation, environmental performance, resource efficiency, and infrastructure development collectively support the objectives of the 2030 Agenda.

7.1 SDG 7: Advancing Affordable, Sustainable Energy Access

Green hydrogen production can contribute significantly to SDG 7 (Affordable and Clean Energy) by supporting the transition from fossil-fuel-based energy systems toward renewable and low-carbon energy sources. Water electrolysis, when powered by renewable electricity, provides a direct pathway for converting solar and wind energy into storable hydrogen. Improvements in electrolyzer efficiency, durability, and operating flexibility can reduce energy consumption and production costs while enhancing the reliability of renewable-energy systems.

Similarly, ethanol steam reforming and biomass gasification can utilize renewable or bio-derived feedstocks to produce hydrogen, potentially reducing dependence on fossil resources. High-temperature thermochemical processes can also utilize renewable heat sources, such as concentrated solar energy, to drive water-splitting reactions. Collectively, these technologies can diversify the energy supply, facilitate renewable-energy integration, and contribute to the development of more sustainable and resilient energy systems.

7.2 SDG 9: Driving Industrial Innovation and Sustainable Infrastructure

Green hydrogen technologies directly support SDG 9 (Industry, Innovation and Infrastructure) by stimulating technological innovation, sustainable industrialization, and the development of new energy infrastructure.

Innovation in water electrolysis, including advanced electrolyzer designs, improved catalysts and membranes, higher current densities, and enhanced system control, can improve hydrogen-production performance while reducing energy consumption. Integration with smart grids and energy-storage systems can further optimize electricity utilization and provide greater flexibility to energy infrastructure.

Ethanol steam reforming combines renewable feedstocks with advanced catalytic and process technologies, creating opportunities to improve hydrogen yield, reduce operating costs, and utilize existing ethanol-production infrastructure. Biomass gasification similarly promotes industrial innovation through the development of advanced gasifiers, gas-cleaning systems, catalysts, and integrated hydrogen-production processes. Meanwhile, high-temperature thermochemical cycles encourage innovation in reactor design, heat management, advanced materials, and high-temperature energy integration. These developments can contribute to more efficient, resilient, and sustainable industrial infrastructure.

7.3 SDG 13: Supporting Climate Mitigation and Resilience

Green hydrogen can contribute to SDG 13 (Climate Action) by reducing the carbon intensity of hydrogen production and supporting the decarbonization of sectors that are difficult to electrify directly.

Advances in water electrolysis can reduce electricity consumption per unit of hydrogen, particularly when electrolyzers are powered by low-carbon renewable electricity. This can decrease lifecycle greenhouse-gas emissions and reduce dependence on fossil-fuel-based hydrogen production.

In ethanol steam reforming, improved catalysts, optimized operating conditions, and higher process efficiency can reduce energy consumption and emissions associated with hydrogen production. When renewable feedstocks are appropriately sourced and carbon flows are effectively managed, the overall environmental performance can be further improved.

Biomass gasification can provide additional climate benefits when sustainable biomass residues or waste materials are used. Furthermore, integration with carbon capture and storage (CCS) or carbon capture and utilization can potentially result in very low or even net-negative greenhouse-gas emissions under suitable feedstock and system conditions.

High-temperature thermochemical processes can also reduce dependence on fossil fuels by utilizing renewable heat sources, such as concentrated solar energy, thereby supporting long-term greenhouse-gas mitigation and the transition toward low-carbon energy systems.

7.4 SDG 12: Promoting Resource-Efficient Production and Consumption

Biomass gasification has particular relevance to SDG 12 (Responsible Consumption and Production) because it can convert biomass residues, agricultural waste, forestry residues, and other organic materials into useful products such as hydrogen and syngas. This approach supports the principles of a circular economy by transforming residual materials into valuable energy resources rather than treating them solely as waste.

The effective integration of biomass supply chains, gasification, syngas cleanup, hydrogen purification, and by-product utilization can improve overall resource efficiency. However, sustainable feedstock sourcing and appropriate environmental management are essential to ensure that biomass utilization does not result in adverse effects on land, water, or ecosystem resources.

7.5 SDG 15: Protecting Terrestrial Ecosystems and Biodiversity

Green hydrogen pathways based on biomass can also contribute to SDG 15 (Life on Land) when biomass feedstocks are obtained through sustainable land and ecosystem management. The use of agricultural and forestry residues can provide an opportunity to recover energy from existing biomass streams while reducing waste.

However, biomass-based hydrogen production must avoid practices that contribute to deforestation, soil degradation, habitat loss, or biodiversity decline. Sustainable sourcing criteria, responsible land management, and appropriate assessment of biomass availability are therefore essential. When these principles are followed, biomass gasification can support both renewable-energy production and the sustainable utilization of terrestrial resources.

7.6 SDG 17: Strengthening Global Partnerships for Sustainable Development

Achieving the full potential of green hydrogen requires strong cooperation among governments, industry, academia, research institutions, financial organizations, and civil society, directly supporting SDG 17 (Partnerships for the Goals).

Government institutions can establish appropriate policies, incentives, safety regulations, and standards, while the private sector can provide investment, technological expertise, and infrastructure-development capabilities. Universities and research organizations contribute through technological innovation, process optimization, demonstration projects, and workforce development. International cooperation is particularly important for developing common hydrogen standards, certification systems, supply chains, and cross-border hydrogen markets.

Such partnerships can accelerate the commercialization of emerging technologies, reduce investment risks, facilitate knowledge transfer, and support the development of hydrogen infrastructure at both national and international scales.

Overall Contribution to the SDGs

The strategic deployment of green hydrogen technologies can therefore contribute to multiple dimensions of sustainable development. Water electrolysis supports renewable-energy integration and clean-energy production; ethanol steam reforming provides opportunities for renewable-feedstock utilization and process integration; biomass gasification promotes resource recovery and circularity; and high-temperature thermochemical processes offer alternative pathways for renewable heat-driven hydrogen production.

However, the contribution of these technologies to the SDGs ultimately depends on how they are implemented, including the source of energy and feedstocks, lifecycle emissions, water and land requirements, material use, economic feasibility, and environmental safeguards. A systems-based approach that simultaneously considers technological, economic, environmental, and social factors is therefore essential.

Overall, green hydrogen represents a potentially transformative pathway for advancing SDG 7, SDG 9, SDG 12, SDG 13, SDG 15, and SDG 17. Through technological innovation, responsible resource management, climate mitigation, sustainable industrialization, and international cooperation, hydrogen technologies can contribute to the broader objectives of the 2030 Agenda for Sustainable Development.

8. Conclusions

This study has comprehensively examined the technological, environmental, economic, and strategic dimensions of green hydrogen production, with particular emphasis on the challenges and opportunities associated with achieving the objectives of the United Nations 2030 Agenda for Sustainable Development. The analysis of different hydrogen-production pathways demonstrates that, although substantial technical and economic barriers remain, green hydrogen offers considerable potential to contribute to the transition toward a sustainable, resilient, and low-carbon global energy system.

Among the technologies examined, renewable-powered water electrolysis represents one of the most promising pathways for large-scale green hydrogen production because of its compatibility with solar and wind energy. At the same time, high-temperature thermochemical processes provide alternative routes for hydrogen production by utilizing renewable or other low-carbon heat sources. Continued advances in electrolyzer design, catalysts, membranes, high-temperature materials, reactor configurations, and process integration will be essential for improving efficiency, durability, scalability, and economic competitiveness.

The analysis also highlights the importance of integrating hydrogen production with broader energy-system infrastructure. Coupling electrolyzers with variable renewable-energy sources, energy storage, smart-grid technologies, and Power-to-Gas systems can improve the utilization of renewable electricity while providing greater flexibility to energy networks. Such integration can facilitate decentralized hydrogen production, reduce renewable-energy curtailment, and strengthen energy security by diversifying energy supply pathways.

An important opportunity identified in this study is the integration of carbon capture and utilization (CCU) with hydrogen-based energy and industrial systems. Captured CO_2 can be utilized as a feedstock for the production of synthetic fuels, chemicals, and other value-added products, thereby promoting circular-carbon approaches and improving resource efficiency. However, the overall environmental benefit of such systems depends on the source of CO_2, the energy requirements of capture and conversion, and the complete lifecycle performance of the integrated process.

The development of efficient hydrogen-storage and transportation technologies is equally important for establishing a flexible hydrogen economy. Advances in compressed and liquid hydrogen systems, metal hydrides, advanced storage materials, and liquid organic hydrogen carriers can improve storage density, safety, transportability, and system flexibility. These developments are particularly important for connecting hydrogen-production regions with industrial and commercial demand centers and for facilitating the emergence of international hydrogen trade.

From a sustainability perspective, green hydrogen can contribute to several SDGs, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 15 (Life on Land), and SDG 17 (Partnerships for the Goals). Its contribution, however, depends on sustainable resource management, renewable-energy availability, responsible biomass sourcing, lifecycle emissions, water requirements, and appropriate environmental and social safeguards.

Despite the considerable progress achieved, several challenges require continued attention. These include high capital costs, energy losses, electrolyzer degradation, critical-material dependence, hydrogen storage and transportation requirements, infrastructure limitations, regulatory uncertainty, and the need for internationally harmonized standards and certification systems. Building resilient supply chains for electrolyzers, catalysts, membranes, and other critical components will also be essential to avoid technological and geopolitical vulnerabilities as global deployment expands.

Therefore, the future development of green hydrogen should follow a systems-oriented and integrated approach rather than focusing exclusively on individual production technologies. Strategic investments should be directed toward technology commercialization, infrastructure development, R&D, workforce development, digitalization, storage, and international supply chains. At the same time, governments and international organizations should establish coherent policies, financial mechanisms, safety standards, and market frameworks that encourage private investment while ensuring environmental sustainability.

In conclusion, green hydrogen represents more than an alternative method of hydrogen production; it has the potential to become a strategic energy carrier and an important component of the global energy transition. By combining technological innovation with renewable-energy deployment, circular-economy principles, carbon utilization, advanced storage, digital technologies, international cooperation, and supportive policies, green hydrogen can help overcome existing barriers while creating new opportunities for economic development and energy security. Its strategic implementation can therefore contribute substantially to the objectives of the 2030 Agenda and support the emergence of a more resilient, decarbonized, interconnected, and sustainable global energy system.

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