

GREEN HYDROGEN & IT'S FUTURE IN

POWER SECTOR

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ABSTRACT

The growing demand for clean, reliable, and sustainable energy systems has significantly increased global interest in hydrogen as a zero-carbon energy carrier. Hydrogen has strong potential to reduce greenhouse gas emissions across both the transportation and power sectors while supporting the transition away from fossil-fuel-based energy systems. This research paper examines the role of hydrogen in enabling a sustainable energy future, with particular emphasis on its integration into modern power systems and its contribution to long-term decarbonization goals.

The study focuses on hydrogen's ability to store surplus renewable energy generated from solar and wind sources through power-to-hydrogen technologies and its reconversion into electricity using hydrogen-to-power systems. This energy pathway provides an effective solution for large-scale and long-duration energy storage, grid stability, peak-load management, and backup power, addressing key limitations of conventional battery storage systems. In addition, the performance of fuel cells and hydrogen combustion technologies is evaluated in terms of efficiency, reliability, and durability for power generation applications.

Furthermore, the paper analyzes the infrastructure requirements for hydrogen production, storage, transportation, and refueling, while identifying technical, safety, and economic challenges associated with large-scale deployment and integration into existing power networks. Emphasis is placed on



cross-sector integration and sector coupling, enabling hydrogen to link the power, transportation, and industrial sectors by utilizing excess electrical energy. Safety aspects, standards, and regulatory frameworks are also reviewed to ensure secure operation and public acceptance, and key research gaps and innovation opportunities in hydrogen production, advanced storage materials, and next-generation fuel cell technologies are pathway provides an effective solution for large-scale and long-duration energy storage, grid stability, peak-load management, and backup power, addressing key limitations of conventional battery storage systems. In

addition, the performance of fuel cells and hydrogen combustion technologies is evaluated in terms of efficiency, reliability, and durability for power generation applications. identified, highlighting hydrogen's critical role in future sustainable power systems.

INTRODUCTION

Global dependence on fossil fuels continues to drive high greenhouse gas emissions, despite 147 countries committing to net-zero targets by 2024. Fossil fuels still supply over 85% of global energy, releasing more than 21 billion tons of CO₂ annually [1], [6]. While renewable sources such as solar and wind are expanding, their intermittent nature and limited storage options prevent them from fully replacing fossil fuels [2], [6]. Hydrogen has therefore gained attention as a promising energy carrier that can support renewable energy systems through long-duration storage and decarbonization of hard-to-electrify sectors such as transportation and heavy industry [1], [3], [4].

Currently, hydrogen production remains largely fossil-fuel-based, with natural gas and coal accounting for the majority of global output [6]. Low-emission hydrogen represents less than 1% of total production, and green hydrogen produced via electrolysis is still minimal, despite recent growth [6], [10]. Conventional hydrogen production emits significant amounts of CO₂, highlighting the urgent need to transition toward cleaner production pathways as global hydrogen demand continues to rise [7], [8]. This review analyzes the current hydrogen landscape, focusing on production technologies, costs, infrastructure, and policy frameworks [1], [2], [5]. By integrating technical, economic, and regulatory perspectives, it identifies key challenges and opportunities for scaling green hydrogen and emphasizes its critical role in enabling a sustainable, low-carbon energy future [6], [9].

GREEN HYDROGEN

➤ GREEN HYDROGEN PRODUCTION TECHNOLOGIES

1. Water Electrolysis for Green Hydrogen Production

Water electrolysis is a widely adopted process for hydrogen production, in which water molecules are split into hydrogen and oxygen using electrical energy. When an electric current is applied, hydrogen gas is generated at the cathode while oxygen gas evolves at the anode. If the electricity used for this process is derived from renewable sources, the resulting hydrogen is classified as green hydrogen, making the process environmentally sustainable and carbon-free [1], [2]. Several types of water electrolysis technologies have been developed to suit different operating conditions and applications. Alkaline water electrolysis, which uses alkaline electrolytes such as potassium hydroxide (KOH) or sodium hydroxide (NaOH), is a mature and cost-effective technology, although it generally operates



at slower reaction rates and lower current densities [1], [10]. Proton exchange membrane (PEM) electrolysis employs a solid polymer electrolyte and offers high efficiency, rapid dynamic response, and compact system design, but its reliance on noble metal catalysts significantly increases system cost [2]. Anion exchange membrane (AEM) electrolysis aims to combine the advantages of alkaline and PEM systems by enabling the use of low-cost catalysts while maintaining relatively high performance; however, it is still under active research and development [10]. Solid oxide electrolysis cells (SOECs) operate at elevated temperatures using steam as the feedstock and achieve very high conversion efficiencies, though long-term durability and material stability remain major challenges [6], [10]. Overall, water electrolysis is considered a key enabling technology for large-scale green hydrogen production, with each method presenting distinct trade-offs related to cost, efficiency, materials, and operating conditions [1], [6].

2. Alkaline and Proton Exchange Membrane Electrolyzers Alkaline electrolytes, such as aqueous KOH or NaOH solutions, have been extensively used in electrolysis systems due to their high ionic conductivity and strong chemical stability. These electrolytes enable the utilization of a wide range of non-precious metal catalysts, making alkaline electrolysis systems economically attractive and scalable for industrial applications [1], [10]. However, alkaline electrolyzers typically exhibit slow electrochemical reaction kinetics and operate at lower current densities, which necessitate large electrode surface areas and result in bulky system configurations [2]. Additionally, the handling of concentrated alkaline solutions poses safety concerns, as these electrolytes are highly corrosive and require stringent measures to prevent leakage and accidental exposure [2]. In contrast, proton exchange membrane (PEM) electrolyzers use solid polymer electrolytes, such as Nafion™, which facilitate efficient proton transport while maintaining excellent gas separation. PEM systems are capable of producing high-purity hydrogen and demonstrate superior efficiency due to rapid reaction kinetics and the ability to operate at high current densities [1]. Furthermore, PEM electrolyzers can function at elevated pressures, thereby minimizing or eliminating the need for external hydrogen compression and improving overall system efficiency [6]. The acidic operating environment can accelerate material degradation and limits the compatibility of low-cost components. Additionally, the dependence on noble metal catalysts such as platinum and iridium substantially increases capital costs, which restricts widespread commercial deployment at large scales .

3. Comparative Assessment of Alkaline and PEM Electrolysis Systems

Alkaline electrolyzers remain a proven and cost-efficient solution for hydrogen production due to their ability to use inexpensive catalysts and well-established system designs [1], [10]. However, their limitations in terms of slow kinetics, lower current densities, and safety concerns related to corrosive electrolytes continue to drive research into alternative technologies [2]. PEM electrolyzers, on the other hand, offer higher efficiency, compact design, and superior operational flexibility, making them attractive for integration with renewable energy systems [6]. Nevertheless, issues related to material durability and high costs associated with noble metals remain major barriers to their large-scale adoption [10]. Consequently, ongoing research efforts are focused on improving catalyst stability, reducing material costs, and developing hybrid systems such as AEM electrolyzers that can bridge the performance and cost gap between alkaline and PEM technologies [1], [10].



➤ INTEGRATION OF GREEN HYDROGEN IN THE POWER SECTOR

1. Energy Storage and Grid Balancing

Green hydrogen enables the storage of surplus renewable electricity that would otherwise be curtailed when solar or wind generation exceeds grid demand. During periods of excess power, electrolyzers convert electrical energy into hydrogen, which can be stored and later reconverted into electricity through fuel cells or turbines when renewable output is low or demand is high. This flexible operational capability supports grid balancing, enhances system reliability, and significantly reduces renewable energy curtailment, especially in power systems with high variable renewable penetration [1], [2], [6].

2. Seasonal and Long-Duration Storage

Unlike electrochemical batteries that are generally limited to short-duration storage ranging from hours to a few days, hydrogen enables long-duration and seasonal energy storage extending from weeks to months with minimal self-discharge losses. Its high gravimetric energy density and suitability for large-scale storage options—such as underground salt caverns and pressurized tanks—make hydrogen an effective solution for managing extended periods of low renewable energy availability, including seasonal variations such as reduced solar generation during winter months [1], [6], [10].

3. Power Generation and Sector Coupling

Hydrogen can be utilized for electricity generation either through high-efficiency fuel cells or by co-firing and blending with natural gas in conventional gas turbines, providing a low-carbon alternative for power generation. Such integration enhances overall energy system efficiency and contributes to substantial greenhouse gas emission reductions across the economy [1], [3], [6].

➤ OPPORTUNITIES AND EMERGING TRENDS

1. Green Steel: From Coke to Hydrogen

Traditional steelmaking is among the world's largest industrial sources of CO₂ emissions, mainly due to the use of coking coal as a reducing agent in blast furnaces. Green hydrogen fundamentally alters this process by eliminating carbon from the reduction chemistry [1], [6]. Hydrogen Direct Reduction (H-DRI):

In the H-DRI route, 100% green hydrogen is used instead of coal or coke to reduce iron ore. The reaction produces water vapour (H₂O) rather than carbon dioxide (CO₂), enabling near-zero direct emissions from the ironmaking stage [1], [10].

Electric Arc Furnace (EAF) Link: The reduced iron, commonly referred to as sponge iron, is subsequently melted in an Electric Arc Furnace powered by renewable electricity, further minimizing indirect emissions from steel production [1], [6].

Impact: This hydrogen-based steelmaking pathway can reduce carbon emissions by up to 90–95% compared with conventional blast furnace–basic oxygen furnace routes [6]. In India, multiple pilot-scale projects have been initiated under the National Green Hydrogen Mission to evaluate the techno-economic feasibility of H-DRI at commercial scale [1], [5].

2. Chemicals and Fertilizers: The “Green Ammonia” Revolution

The chemical and fertilizer industry is currently the largest consumer of hydrogen worldwide; however,



nearly 99% of this hydrogen is produced from fossil fuels, primarily via steam methane reforming, resulting in substantial CO₂ emissions [2], [6]. Green hydrogen enables the production of green ammonia, forming the basis of carbon-neutral fertilizers.

Haber–Bosch Decarbonization: Conventional ammonia synthesis emits approximately 1.8–2 tonnes of CO₂ per tonne of ammonia produced. By replacing fossil-based hydrogen with green hydrogen generated through water electrolysis and combining it with nitrogen separated from air, ammonia production can become virtually carbon-free [2], [10].

Methanol Production: Green hydrogen can also be combined with captured CO₂ to synthesize green methanol, which serves as a sustainable feedstock for the chemical industry and a potential low-carbon fuel for maritime transport [6], [10].

India’s Focus: To decarbonize its domestic fertilizer sector, India has recently auctioned long-term supply contracts for approximately 7.24 lakh metric tonnes of green ammonia per year, reflecting strong policy support for large-scale adoption of green hydrogen in chemical manufacturing [1], [5], [6].

3. **Petroleum Refining: Cleaning Up Traditional Fuels** Petroleum refineries consume large quantities of hydrogen for desulfurization processes and for upgrading heavy crude fractions into lighter transportation fuels. At present, this hydrogen is predominantly produced on-site using steam methane reforming, contributing significantly to refinery Scope 1 and Scope 2 emissions [2], [6].

4. **Replacing Captive Hydrogen:** Substituting fossil-derived captive hydrogen with green hydrogen can immediately reduce the carbon footprint of refinery operations without major modifications to existing process units [6], [10].

Synthetic Fuels: Refineries can further utilize green hydrogen to synthesize e-fuels, such as synthetic kerosene or diesel, which are chemically similar to conventional fuels but can achieve near-carbon-neutral operation when produced using renewable electricity and captured CO₂. These fuels offer a promising decarbonization pathway for hard-to-abate sectors such as long-haul aviation [6], [10]

➤ CHALLENGES AND LIMITATIONS

1. Economic Barriers: The Cost Gap

The high cost of green hydrogen—often referred to as the “green premium”—remains the most significant economic barrier to its large-scale deployment and is the primary reason grey hydrogen produced from fossil fuels still dominates nearly 99% of the global hydrogen market. As of 2026, the levelized cost of green hydrogen production is estimated to be in the range of USD 4–5 per kg, mainly due to high electrolyzer costs and renewable electricity prices, whereas grey hydrogen produced via steam methane reforming typically costs USD 1.5–2 per kg [2], [6], [10]. To address this disparity, global initiatives such as the “1-1-1” target aim to achieve hydrogen production at USD 1 per kg within one decade, contingent on large-scale electrolyzer deployment, declining renewable energy costs, and supportive policy frameworks [1], [6]. Achieving this cost parity is widely recognized as critical for accelerating the transition toward green hydrogen across the power and energy sectors [1], [10].

2. Infrastructure and Safety: The “Smallest Molecule” Problem

Hydrogen’s unique physical and chemical properties pose major challenges for infrastructure

development, often earning it the reputation of being one of the most difficult gases to handle. Due to its extremely small molecular size, hydrogen is prone to leakage through seals, joints, and materials that are otherwise impermeable to natural gas [2], [3]. A major concern associated with hydrogen transport and storage is hydrogen embrittlement, a phenomenon in which hydrogen atoms diffuse into the crystal lattice of metals—particularly steel—leading to reduced ductility, increased brittleness, and a higher risk of cracking and structural failure in pipelines and storage vessels [1], [2]. These safety and material compatibility challenges necessitate significant upgrades to existing gas infrastructure or the development of hydrogen-specific pipelines and storage systems, increasing overall deployment costs [1], [6].

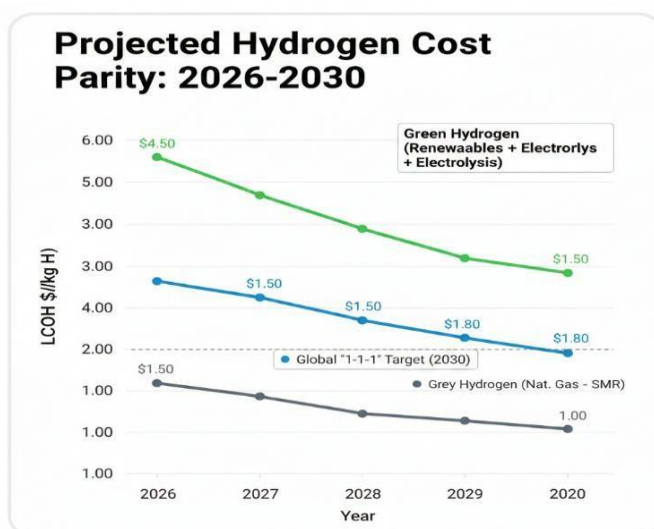


Figure 1 : Chart comparing Levelized Cost of Hydrogen (LCOH) for Green, Blue, and Grey pathways through 2030

Storage Density: To store a useful amount of energy, hydrogen must be either compressed to extreme pressures (350–700 bar) or liquefied at cryogenic temperatures (-253°C). Both processes are energy-intensive, consuming up to 30% of the energy contained in the hydrogen itself.

Safety Protocols: Hydrogen has a wide flammability range and a near-invisible flame. Detection requires specialized UV/IR sensors rather than traditional heat or smoke detectors. Storage Density to store a practically useful amount of energy, hydrogen must be either compressed to very high pressures (typically 350–700 bar) or liquefied at cryogenic temperatures of approximately -253 °C. Both compression and liquefaction are highly energy-intensive processes, together accounting for energy losses of up to 30% of the total energy content of hydrogen. These storage constraints represent a significant technical and economic challenge for large-scale hydrogen deployment in power and energy systems [1], [2], [6], [10].

Hydrogen Storage Methods



Figure 2 : : Infographic showing hydrogen storage methods: High-pressure tanks vs. Liquid H₂ vs. Salt Caverns

➤ FUTURE OUTLOOK

1. Advanced Electrolyzer Technologies

Efficiency improvement and cost reduction are the primary drivers shaping green hydrogen deployment toward 2030. While alkaline and proton exchange membrane (PEM) electrolyzers currently dominate the commercial market, several next-generation technologies are rapidly reaching technological and commercial maturity [1], [2], [10].

Anion Exchange Membrane (AEM) electrolyzers are increasingly regarded as a hybrid solution that combines the low material cost and non-precious metal catalysts of alkaline systems with the high current density, rapid load-following capability, and compact design of PEM electrolyzers.

When integrated with industrial waste heat sources from sectors such as steelmaking or chemical processing, SOEC systems can achieve electrical efficiencies approaching 90%, significantly surpassing the 60–70% efficiency range of conventional low-temperature electrolyzers [2], [6], [10].

2. Hydrogen as a Grid Stabilizer

As electrical grids transition toward high or near-100% renewable energy penetration, green hydrogen is emerging as a critical solution for long-duration energy storage (LDES), addressing limitations associated with short-duration battery storage [1], [6].

While lithium-ion batteries are well suited for short-term balancing over durations of 4–8 hours, hydrogen enables energy storage over weeks to months with minimal self-discharge. This characteristic enables seasonal energy shifting, where excess solar generation during summer periods can be converted into hydrogen, stored in large underground formations such as salt caverns, and reconverted into electricity during periods of low renewable output, particularly in winter [1], [2], [6].



3. Policy and Global Trade Hubs

The future outlook for green hydrogen is increasingly shaped by international policy frameworks, cross-border trade mechanisms, and large-scale government incentive programs [1], [6]. Countries with abundant renewable resources and large land availability—including India, Australia, and Chile—are positioning themselves as global hydrogen production and export hubs. Under India’s National Green Hydrogen Mission, a domestic production target of 5 million metric tons (MMT) per year by 2030 has been announced, supported by incentive allocations of approximately ₹20,000 crore to promote electrolyzer manufacturing, renewable integration, and downstream hydrogen utilization [5], [6].

Table 1 : Summary of 2030 Impact

Feature	Today (2025/26)	Future Outlook (2030+)
Primary Tech	Alkaline / PEM	AEM / High-Temp SOEC
Grid Role	Pilot / Testing	Large-scale Seasonal Storage
Cost	\$4–\$5/kg	\$1.50–\$2/kg (Target)
Main Use	Refining / Fertilizers	Steel / Shipping / Heavy Grid Support

CONCLUSION

The transition to a hydrogen-based economy represents a transformative pathway toward deep decarbonization across multiple sectors, including heavy industry, transportation, and power generation. Green hydrogen, produced via water electrolysis powered by renewable energy, holds immense promise as a clean and sustainable energy carrier. However, its large-scale deployment faces persistent economic, technological, and infrastructural challenges. High production costs, limited electrolyzer efficiency, supply chain constraints, and the complexity of hydrogen storage and transport remain major barriers. While global hydrogen production is currently dominated by fossil fuel-based methods, concerted efforts in research, policy, and market expansion are driving momentum toward a hydrogen economy centered on renewable energy sources. Despite these challenges, the global landscape for green hydrogen is rapidly evolving. Major nations such as the European Union, the United States, China, Japan, Australia, and the Middle East have launched ambitious hydrogen strategies, with substantial investments in infrastructure, research, and market incentives. Electrolyzer manufacturing capacity is expanding, and hydrogen hubs are emerging worldwide to facilitate production and distribution. However, achieving cost competitiveness with fossil fuel-derived hydrogen remains a major challenge. The levelized cost of green hydrogen, currently ranging from USD 5.0–10.0/kg H₂, must be significantly reduced to ensure widespread adoption. Projections suggest that costs could fall below USD 2/kg H₂ by the 2040s, driven by advancements in electrolyzer technologies, production scale, and the declining cost of renewable electricity.



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