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A Study on Green Hydrogen in the Power Sector

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Abstract

In the global shift to a sustainable and decarbonized power sector, green hydrogen—produced by electrolyzing water using renewable energy sources like solar, wind, and hydropower—has become a crucial option. As nations intensify efforts to meet climate targets and reduce reliance on fossil fuels, green hydrogen offers a versatile energy carrier capable of addressing key challenges, including energy storage, grid balancing, and deep decarbonization of hard-to-abate sectors. This paper explores the integration of green hydrogen into the power sector, analyzing its technical feasibility, economic viability, and environmental benefits. It examines the current state of electrolyzer technologies, renewable energy coupling strategies, and infrastructure requirements for large-scale deployment. The integration of green hydrogen into the contemporary power industry is thoroughly evaluated in this article, with an emphasis on its economic viability, environmental sustainability, and technological feasibility. It examines the efficiency, prices, scalability, and operational limitations of important electrolyzer technologies, including proton exchange membrane (PEM), alkaline, solid oxide, and anion exchange membrane systems, as well as their prospects for the future. Additionally, the study assesses renewable energy coupling techniques, emphasizing their importance in maximizing hydrogen generation. These techniques include direct integration with solar and wind farms, hybrid systems, and off-grid applications. Case studies from leading regions such as Sweden, Australia, and Denmark demonstrate early successes and emerging best practices. Despite challenges related to high production costs, energy efficiency losses, and infrastructure gaps, the synergy between plummeting renewable energy prices and advancing electrolysis technologies signals a transformative potential for green hydrogen. Strategic policy support, international collaboration, and public-private investment are identified as critical enablers in accelerating adoption.

Keywords: Green energy, hydrogen, alkaline electrolyzer, polymer electrolyzer, power sector, electrolytic process, renewable energy

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INTRODUCTION

The exponential decline in the levelized cost of electricity (LCOE) from solar-photovoltaic (PV) and onshore/offshore wind has accelerated the displacement of thermal generation. However, the intrinsic intermittency of these variable renewable energy (VRE) resources imposes a residual reliability gap that must be bridged to preserve grid adequacy. Green hydrogen, which is produced by water electrolysis powered exclusively by renewable electricity, offers a high-energy-density and - long-duration storage medium capable of converting surplus VRE into a chemically stable carrier. When coupled with power-to-gas (P2G) conversion, fuel cell based combined-cycle gas turbines (CCGT), or direct hydrogen fuel cell (HFC) power blocks, green hydrogen can provide both capacity and energy services, including firm capacity, frequency regulation, and seasonal storage [1–3].

Green hydrogen, produced via renewable-powered water electrolysis, is a crucial zero-emission energy carrier for decarbonizing the power sector, storing energy, and replacing natural gas in turbines. They facilitate grid stability and provide long-duration storage, with costs projected to decline by 40-80% as renewable energy becomes cheaper [4].

Green hydrogen is a zero-emission, clean energy carrier produced using renewable electricity (solar, wind, and hydro) to split water into hydrogen and oxygen through electrolysis. They act as sustainable, flexible energy storage media in the power sector, which is critical for reducing dependency on fossil fuels, managing intermittent renewable energy sources, and driving decarbonization to achieve net-zero goals [5–7].

Key aspects of green hydrogen in the power sector:

- *Production process:* Water electrolysis (using proton exchange membrane (PEM) or alkaline electrolyzers) splits $2O$ into $H2$ and O_2, creating a high-energy, carbon-free fuel.
- *Energy storage and flexibility:* Green hydrogen can store surplus renewable energy for long durations, offering solutions to seasonal fluctuations and to grid instability.
- *Decarbonization:* It offers a path to replace gray hydrogen (produced from natural gas) in industrial processes and acts as a clean fuel for transport, power generation, and chemical production (e.g., green ammonia).
- *Global/national strategies:* Countries such as India, through the National Green Hydrogen Mission, are scaling up production and developing infrastructure to reduce costs and foster a sustainable, self-reliant energy economy.
- *Challenges:* Current obstacles include high production costs, the need for significant capital investment, and the requirement for improved storage and transportation infrastructure.

As technology matures, the cost of green hydrogen is expected to decrease, making it a cornerstone of the global transition to a sustainable, low-carbon energy system. This briefing synthesizes the state-of-the-art electrochemical pathways, techno-economic metrics, and grid-integration architectures, employing the rigor expected of a power-system engineer or energy-policy analyst [8]. The electrochemical production of green hydrogen in the power sector involves splitting water into hydrogen and oxygen using electricity from renewable sources (wind, solar, and hydro) via electrolyzers.

Key technologies, as shown in Table 1 and Figure 1, include alkaline electrolysis (AEL) for large-scale applications, PEM for flexibility, and emerging solid oxide electrolyzer cells (SOEC) for high efficiency.

- *Proton exchange membrane electrolysis:* Operates at low temperatures (30–-80°) with high current densities, allowing a rapid response to intermittent renewable energy. It produces high-purity hydrogen (99.999% purity).
- *Alkaline water electrolysis (AEL):* A mature, cost-effective technology often used for large-scale production and suitable for steady power inputs.
- *Solid oxide electrolyzer cells:* Operate at high temperatures (>600°C) and achieve higher efficiencies (>80%) by reducing electrical energy consumption through the incorporation of thermal energy input.
- *Anion exchange membrane (AEM) electrolysis:* Combines the advantages of low-cost materials (such as AEL) with the flexibility of PEM and is currently being developed for better cost efficiency.

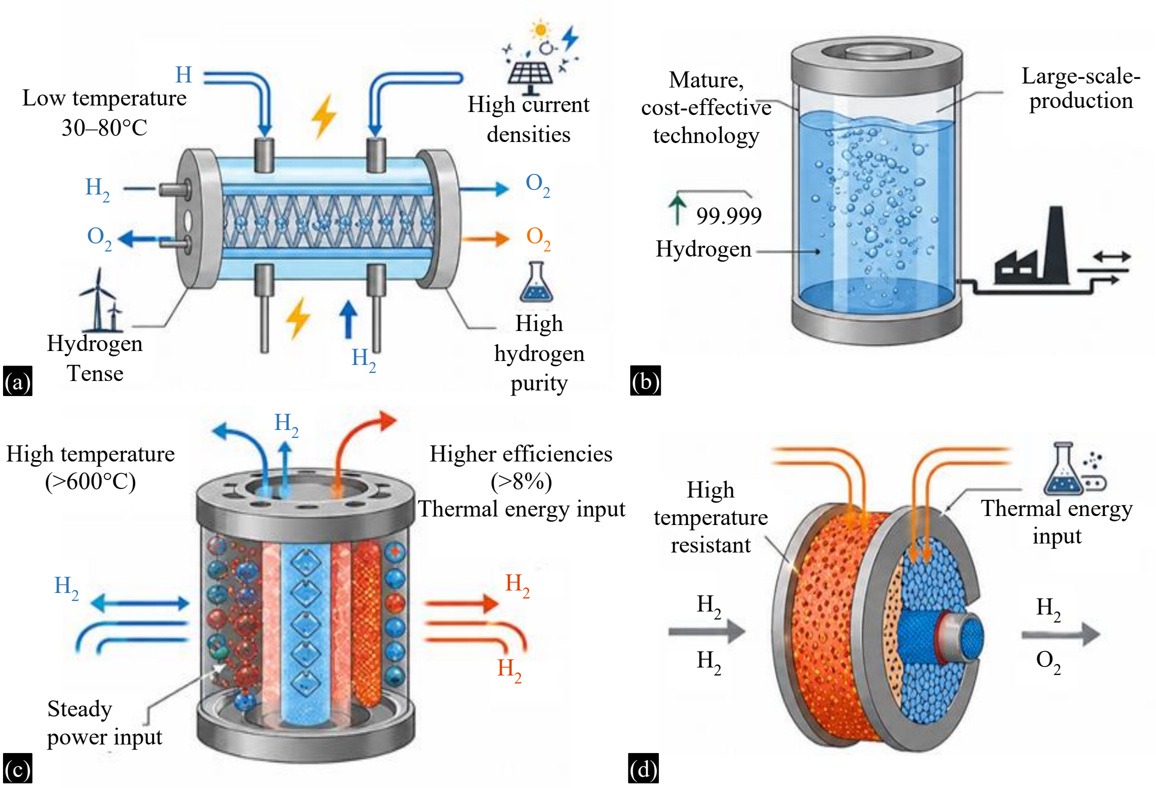

Figure 1. (a)–(d) Key technologies. (a) PEM electrolysis; (b) Alkaline water electrolysis (AEL); (c) Solid oxide electrolyzer cells (SOEC); (d) Anion exchange membrane (AEM) electrolysis.

Table 1. Key technologies.

Technology	**Core chemistry**	**Typical operating conditions**	**Round-trip efficiency***
Alkaline electrolyzer (AEL)	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	60–80°C, 30–40 bar	65–70%
Polymer electrolyte membrane (PEM) electrolyzer	$H_2O \rightarrow ½ O_2 + H_2$	50–80°C, 30–100 bar, 0.6–1 A cm^{-2}	70–78%
Solid oxide electrolyzer (SOE)	$H_2O \rightarrow ½ O_2 + H_2$ (via O^{2-} transport)	650–850°C, 10–30 bar	80–85% (when co-electro-thermal)

**Round-trip efficiency = (HHV of H_2 produced)/(electrical energy consumed).*

Key Technical Levers

1. *Current density (J):* Directly influences the specific power (kW kg^{-1} H_2). PEM systems can sustain >1 A cm^{-2}, reducing the stack footprint but penalizing durability (membrane degradation, catalyst sintering).
2. *Catalyst loading:* Pt-group metals (PGM) dominate PEM anodes; non-PGM alternatives (Ni–-Mo, Co–-Fe spinels) are under intensive research and development to cut CAPEX.
3. *Mass transport:* Bubble-induced pressure drop and electrolyte conductivity dictate optimal cell geometry; high-frequency pulsated flow improves gas removal and mitigates flooding.

STRUCTURE FOR EMBEDDING GREEN HYDROGEN INTO THE POWER SECTOR

The structure for embedding green hydrogen into the power sector has seven layers. Table 2 and Figure 2 show the layered structure and functions along with key aspects. The basic components for green hydrogen power are:

- *Production (supply side):* Electrolysis facilities powered by dedicated renewable energy sources utilizing Alkaline, PEM, or Solid Oxide technologies.
- *Storage and transport:* Compressed gas or liquid hydrogen is stored in caverns or tanks, allowing long-term, large-scale energy storage.

- *Application (demand side):* Utilization for grid balancing, fuel cells, or industrial processes (ammonia and steel) [9, 10].
- *Infrastructure:* Integration with existing transmission networks (Green Energy Corridors) to connect renewable hotspots to production hubs.

Each layer is interdependent, and the performance envelope of the entire system is defined by the weakest link. Therefore, the design philosophy emphasizes modularity (to replace or upgrade subsystems) and standardization (to ensure interoperable integration).

DISCUSSION

The integration of green hydrogen into the power sector is poised to redefine energy systems, offering a scalable, decarbonized solution to balance intermittent renewable energy, store excess energy, and provide dispatchable power. As global decarbonization targets tighten, the anticipated results of green hydrogen deployment, driven by electrochemical and thermodynamic innovations, hinge on advancing electrolysis efficiency, optimizing storage and conversion technologies, and harmonizing with grid infrastructure. Here is a technical assessment of the expected outcomes:

Electrolyzer Efficiency Gains and Cost Reductions

Green hydrogen production relies on water electrolysis powered by renewable electricity (solar and wind) to split H_2O into H_2 and O_2. Current PEM and alkaline electrolyzers achieve efficiencies of 70–80% (LHV basis), with emerging solid oxide electrolysis (SOEC) promising 85–90% efficiency under high-temperature operations (600–1000°C).

Table 2. Layers for embedding green hydrogen into the power sector.

Layer	Primary function	Representative technologies	Key technical metrics
Generation and grid interface	Supply renewable electricity; manage bidirectional power flows	Utility-scale PV, offshore wind, hybrid solar-wind-storage farms, HVDC interconnectors	Capacity factor (>45 %); Ramp rate (MW/s); Grid code compliance
Electrolytic conversion hub	Convert electrical energy to chemical energy	PEM (Proton-Exchange Membrane), Alkaline, SOEC (Solid-Oxide Electrolyzer) stacks; Power electronics (IGBT/SiC inverters)	Specific energy consumption (kWh/kg H_2); Stack efficiency (65-80 %); Dynamic response (<1 s)
Hydrogen conditioning and compression	Raise pressure, remove impurities, prepare for transport or storage	Pressure swing adsorption (PSA), membrane separation, cryogenic liquefiers, high-pressure compressors (up to 700 bar)	Purity (≥99.97 % per ISO 14687); Compression power ratio (kW/kg H_2); Heat recovery efficiency
Transport and distribution network	Move hydrogen from the hub to end-use points	Steel pipelines (class 1–3), composite-wrapped pipelines, tube-trailers, liquefied hydrogen carriers, ammonia synthesis for maritime transport	Pipeline pressure (15–70 MPa); Leakage rate (<0.1 %/1000 km); Energy density (LHV, 120 MJ/kg)
End-use conversion assets	Convert hydrogen back to electricity or fuel	Fuel-cell power plants (FC-PP), hydrogen-fueled gas turbines (H_2-GT), combustion-based CHP, synthetic fuel synthesis (Fischer-Tropsch)	Electrical efficiency (FC-PP 55-60 %; H_2-GT 45-50 %); Start-up time (<5 min); Emission profile ($CO_2 \approx 0$)
Digital and control layer	Real-time optimization, safety, market participation	SCADA, EMS, DERMS, AI-driven predictive dispatch, digital twins, blockchain-based transaction ledgers	Latency (<100 ms); Forecast horizon (24 h to 1 year); Cyber-security compliance (NERC-CIP)
Regulatory and market interface	Define tariffs, certification, and ancillary service markets	Green-hydrogen certification schemes, capacity market participation, and carbon-pricing mechanisms	LCOH target (<$2.5/kg by 2030); Capacity credit (MW-h per kg)

**CHP: Combined heat and power*

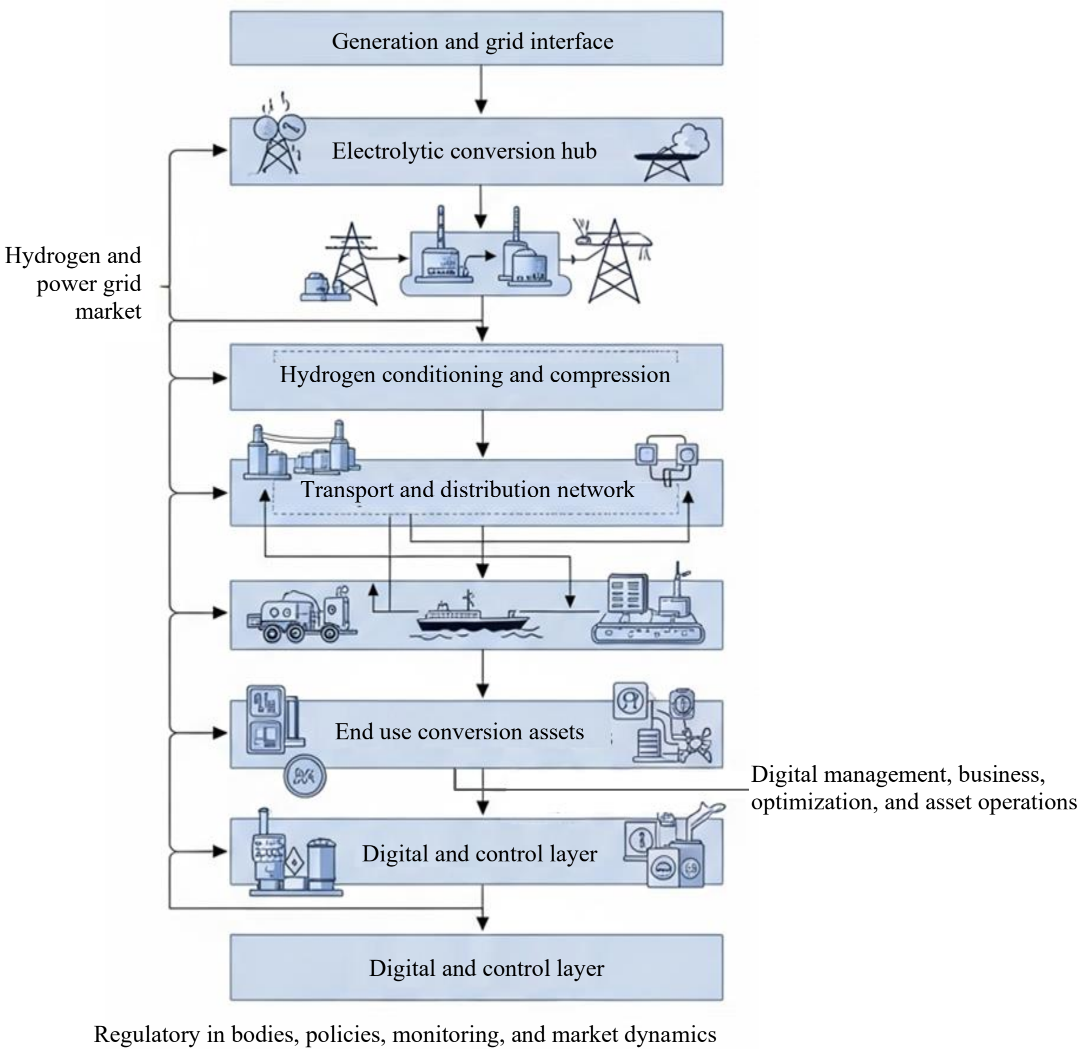

Figure 2. Layered structure.

By 2030, advancements in catalysts (e.g., iridium-free PEM, non-precious-metal SOEC) and system design (modular stacks, AI-driven thermal management) are projected to reduce capital expenditures (CapEx) from \$650/kW to below \$300/kW (IRENA, 2023). This decline will enable electrolyzers to operate profitably at 50–70% capacity factors, even in regions with suboptimal renewable energy (RE) availability.

Grid Decoupling and Long-Duration Storage

One of the most transformative impacts of green hydrogen lies in its ability to decouple electricity generation from demand. Excess RE, currently curtailed during high wind/solar periods, can be converted to hydrogen and stored in high-pressure tanks, salt caverns, or sub-seabed reservoirs, offering multi-day to seasonal storage. When converted back to electricity via hydrogen fuel cells (35–50% efficiency) or modified gas turbines (45–60% with hybrid combustion), it provides a lifeline for grid stability during low RE output. Simulations by the National Renewable Energy Laboratory (NREL) suggest that hydrogen storage systems could reduce renewable curtailment by 80% and lower the system-level LCOE by 15–25% in high-penetration RE grids.

Hydrogen Blending and Power-to-X (PtX) Integration

Hydrogen blending in natural gas pipelines (10–20% H_2 by volume) is expected to mitigate gas-fired power plant emissions while maintaining the system inertia. Advanced blends (30–100% H_2) in turbines and fuel cells, which are currently undergoing certification by the international electrotechnical commission (IEC) and ISO, could eliminate CO_2 emissions. Meanwhile, Power-to-X (PtX) hubs, which couple hydrogen with carbon capture, will produce synthetic fuels (e.g., methanol and ammonia) for the industrial and maritime sectors, indirectly supporting the power grid by offloading hydrogen demand from direct power generation.

Dynamic System Flexibility and Ancillary Services

Hydrogen can act as a "virtual battery" that responds to real-time grid signals. For instance, PEM electrolyzers with rapid start-stop capabilities (sub-minute response times) can regulate frequency by modulating the load during grid imbalances. Similarly, hydrogen-fueled turbines, which operate as synthetic inertia providers, can stabilize the grid frequency faster than traditional synchronous generators. The International Energy Agency (IEA) estimates that hydrogen-based flexibility could reduce the need for natural gas peaker plants by 30% by 2040, accelerating the phase-out of fossil fuels in power.

Despite its promise, green hydrogen faces the following hurdles.

Efficiency Gaps

The round-trip efficiency (grid-to-hydrogen-to-grid) of hydrogen systems typically ranges from 30% to 40%, lagging behind battery efficiency (80–90%). This energy loss underscores the need for high-purity water and advanced catalyst systems to minimize the overpotential in electrolysis.

Cost Barriers

Current production costs hover around $6–$7/kg, driven by renewable electricity prices (the largest cost component) and electrolyzer capital expenditures (approximately $400–$900/kW). While costs are projected to fall to $2–$3/kg by 2030 via economies of scale and catalyst innovations (e.g., ruthenium-free materials), infrastructure investments for hydrogen networks remain a significant bottleneck.

Scalability

Meeting the IEA 2050 2.5 TWh/year target requires 120,000+ GW of electrolyzer capacity—a 1,500x increase from 2023 levels. This demands the vertical integration of renewables, electrolysis, and storage, supported by policy mechanisms such as carbon pricing and hydrogen certification schemes.

CASE STUDIES ON GREEN HYDROGEN IN THE ENERGY REVOLUTION

In the global pursuit of decarbonization, few innovations shine as bright and promising as green hydrogen. No longer a theoretical dream, it is now a tangible solution emerging at the intersection of RE and clean fuel technology. As nations seek alternatives to fossil fuels, particularly in hard-to-abate sectors such as heavy industry and long-duration energy storage, green hydrogen is stepping into the spotlight, especially within the power sector. This article dives into three groundbreaking case studies that reveal how green hydrogen is transforming electricity systems worldwide.

HyBalance, Denmark—Bridging Renewables and Grid Stability

Location: Hobro, Denmark
Year initiated: 2018
Project leads: Air Liquide, GE Renewable Energy, and Danish Energy Agency

Denmark, a pioneer in wind energy, faces a perennial challenge: what to do with excess wind power during periods of high generation and low demand. Enter the HyBalance project—a EUR 15 million initiative designed to convert surplus renewable electricity into green hydrogen using a 1.2 MW PEM electrolyzer.

The hydrogen produced was not only stored but also actively injected into local industrial processes and used to fuel hydrogen-powered vehicles. However, beyond these outputs, the project demonstrated a crucial function: grid balancing. By using hydrogen production as a "load" during peak wind availability, HyBalance reduced the strain on the grid and curtailed energy waste.

Key Impact: The project achieved over 8,000 h of near-continuous operation and proved that green hydrogen could serve as a flexible, real-time grid support tool. This success has inspired similar balancing projects across Scandinavia, cementing the role of green hydrogen in smart, renewable-integrated power systems.

The Hydrogen Valley Initiative, Australia—From Mine to Microgrid
Location: Pilbara Region, Western Australia
Year initiated: 2020
Project leads: Fortescue Future Industries, CSIRO, and Western Power

Australia's sun-drenched outback offers vast solar potential; however, the region's remote mining operations rely heavily on diesel generators. The Hydrogen Valley project flips this script by establishing an integrated green hydrogen ecosystem, where solar and wind power feed large-scale electrolyzers.

In Pilbara, a 250 MW solar farm and 100 MW wind farm provide electricity to produce green hydrogen, which is then used in two ways: first, to power HFC generators that replace diesel in mining operations, and second, to supply a localized microgrid serving nearby communities.

Power Sector Innovation
Perhaps the most revolutionary is the hydrogen-based "island grid" concept. During extended outages or periods of low solar/wind energy, the stored hydrogen is converted back into electricity through fuel cells or turbines, providing reliable, zero-emission backup power**.** This resilience is a game-changer for regions far from centralized grids.

Key Impact
The project is projected to eliminate 300,000 tons of CO_2 annually and reduce electricity costs by 30% in the target zones. It also serves as a blueprint for deploying green hydrogen in remote and off-grid power systems worldwide.

H2 Green Steel and Vattenfall—Electrifying Heavy Industry with Green Power
Location: Norrbotten County, Sweden
Year initiated: 2021
Project leads: H2 Green Steel, Vattenfall, and SSAB

Although primarily an industrial initiative, the H2 Green Steel project exemplifies how green hydrogen can reshape the energy demand and supply dynamics in the power sector. To produce steel without coal, the company uses green hydrogen to reduce iron ore, a process that requires massive amounts of clean electricity.

Vattenfall, Sweden's state-owned utility, is building dedicated wind and solar farms (totaling over 4 TWh/year) to power a 100 MW electrolysis plant, which is set to be the largest in Europe. The project is intertwined with grid upgrades and advanced demand-response systems to manage fluctuating loads.

Power Sector Synergy
This initiative is forcing a rethinking of long-term power planning. Instead of viewing hydrogen production as a passive consumer, the Swedish grid integrates it as a flexible dispatchable load**.** During high renewable output, electrolyzers run at full capacity, and during low output, they scale down, stabilizing the grid.

Key Impact

Once operational, the project is expected to displace 2 million tons of CO_2 per year, which is equivalent to removing nearly 1 million cars from the road. Moreover, it is accelerating investments in Nordic transmission infrastructure and setting a precedent for industrial consumers to co-drive RE development.

CONCLUSION

Green hydrogen stands at the confluence of innovation and necessity, offering a scalable pathway to a resilient, low-carbon power sector. Unlike conventional hydrogen derived from natural gas, green hydrogen generates zero carbon emissions during production, positioning it as the cornerstone of net-zero energy systems. Its dual role as both an energy storage medium and clean fuel enables the stabilization of intermittent renewable generation while supporting the electrification of industrial and transportation processes. Rapid improvements in electrolyzer efficiency combined with declining RE costs are narrowing the competitiveness gap, even though logistical and financial obstacles still exist. The successful integration of green hydrogen will require coordinated investments in transmission, storage, and end-use infrastructure, along with supportive regulatory frameworks that incentivize clean energy innovation. As the power sector evolves beyond mere electricity generation toward an integrated energy ecosystem, green hydrogen emerges not as a distant promise but as an imminent catalyst for transformation. By harnessing this molecule of the future, the world is inching closer to a cleaner, more secure, and sustainable energy tomorrow.

REFERENCES

1. Shemyakina AA, Levina AI, Korablev VV, Lepekhin AA. Architecture of the management system for hydrogen production at hydropplications. Int J Hydrogen Energy. 2024;69:1227–1235. doi:10.1016/j.ijhydene.2024.05.086.
2. Stöckl F, Schill WP, Zerrahn A. Optimal supply chains and power sector benefits of green hydrogen. Sci Rep. 2021;11(1):14191. doi:10.1038/s41598-021-92511-6. PubMed: 34244545.
3. Kirchem D, Schill WP. Power sector effects of green hydrogen production in Germany. Energy Policy. 2023;182:113738. doi:10.1016/j.enpol.2023.113738.
4. Ruhnau O, Schiele J. Flexible green hydrogen: The effect of relaxing simultaneity requirements on project design, economics, and power sector emissions. Energy Policy. 2023;182:113763. doi:10.1016/j.enpol.2023.113763.
5. Bayrakdar Ates EB, Calik E. Public awareness of hydrogen energy: A comprehensive evaluation based on statistical approach. Int J Hydrogen Energy. 2023;48(24):8756–8767. doi:10.1016/j.ijhydene.2022.12.070.
6. Oliveira AM, Beswick RR, Yan Y. A green hydrogen economy for a renewable energy society. Curr Opin Chem Eng. 2021;33:100701. doi:10.1016/j.coche.2021.100701.
7. Longoria G, Lynch M, Curtis J. Green hydrogen for heating and its impact on the power system. Int J Hydrogen Energy. 2021;46:26725–26740. doi:10.1016/j.ijhydene.2021.05.171.
8. Yang B, Zhang R, Shao Z, Zhang C. The economic analysis for hydrogen production cost towards electrolyzer technologies: Current and future competitiveness. Int J Hydrogen Energy. 2023;48(37):13767–13779. doi:10.1016/j.ijhydene.2022.12.204.
9. Goodarzi M, Li Q. Exploring green hydrogen applications and optimization methods in the power sector: a comprehensive review [preprint]. 2024 Jan 10. TechRxiv. doi:10.36227/techrxiv.170491490.08174705/v1.
10. Erdemir D, Dincer I. Development of renewable energy based green hydrogen and oxygen production and electricity generation systems for sustainable aquaculture. J Clean Prod. 2024;434:140081. doi:10.1016/j.jclepro.2023.140081.

