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The role of renewable energy scaling in securing affordable green Hydrogen for India

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Abstract
India's statutory commitment to achieving net-zero greenhouse gas emissions by 2070 and energy independence by 2047 hinges critically on the deep decarbonisation of its heavy, hard-to-abate industrial sectors. Green hydrogen (GH_2), generated through the electrolysis of water powered exclusively by renewable energy sources, and represents a foundational technological framework to substitute carbon-intensive grey hydrogen. However, the economic viability of GH_2 remains constrained by elevated levelized costs of production, where renewable electricity acquisition and transmission tariffs constitute roughly 60% to 70% of the total financial input. This review paper critically evaluates the mechanical and economic dynamics of scaling India's renewable energy (RE) infrastructure to systematically compress GH_2 production costs towards the competitive threshold of $1–2 per kilogram. Evaluating the strategic mandates of India's National Green Hydrogen Mission (NGHM), which targets an annual production of 5 million metric tonnes (MMT) supported by 125 gigawatts (GW) of integrated RE capacity by 2030, this paper explores the techno-economic intersections of solar-wind hybridization, supply-chain localization, and regulatory framework optimization. We isolate and analyze key operational friction points, including high capital expenditure (CAPEX) for advanced electrolyzers, significant regional water scarcity risks, grid transmission inefficiencies, and acute supply-chain dependencies on critical raw materials such as nickel, iridium, and platinum. Finally, this review delineates actionable policy, technological, and infrastructural roadmaps designed to construct an integrated, resilient, and economically self-sustaining green hydrogen value chain within the Indian sub-continent.

Keywords: Green hydrogen, renewable energy scaling, techno-economic analysis, National Green Hydrogen Mission, electrolyzer cost optimization, environmental policy, decarbonisation

Introduction

Global anthropogenic greenhouse gas (GHG) emissions have accelerated climatic instabilities, necessitating a rapid structural transition from fossil-fuel dependencies to clean, decoupled and sustainable energy carriers. While the rapid commercial deployment of solar photovoltaic (PV) systems and onshore wind turbines has successfully decarbonizes significant shares of the decentralized electricity sector, macro-industrial domains remain deeply unsuited for direct electrification. These "hard-to-abate" sectors specifically chemical refining, steel production, heavy-duty maritime transport, and ammonia fertilizer synthesis collectively account for a dominant share of India's industrial carbon emissions. To bypass this technological barrier, hydrogen has emerged as a critical chemical vector capable of functioning simultaneously as a zero-carbon fuel, an industrial feedstock, and a long-duration energy storage medium [1,2].

Currently, India stands as one of the world's largest producers and consumers of hydrogen, utilizing approximately 6.5 to 7.0 MMT of hydrogen annually. However, over 99% of this volume is categorized as grey hydrogen, synthesized via Steam Methane Reforming (SMR) of imported natural gas or coal gasification. This conventional process releases approximately 9 to 12 kilograms of carbon dioxide (CO_2) for every kilogram of hydrogen produced. Conversely, green hydrogen (GH_2), produced via the electrochemical splitting of water molecules utilizing emission-free renewable electricity, offers a pathway to achieve absolute lifecycle carbon neutrality. Recognizing this potential, the Government of India launched the National Green Hydrogen Mission (NGHM) to catalyze domestic manufacturing and deploy supply infrastructure [3]. India has successfully transitioned from conceptual planning to baseline execution, commissioning initial industrial-scale GH_2 capacities. Despite this operational progress, the commercial expansion of GH_2 faces a severe macroeconomic challenge, market price disparity. While grey hydrogen can be reliably produced at a localized cost of $1.50 to $2.00 per kilogram, the production cost of GH_2 in India fluctuates between $4.00 and $6.00 per kilogram [4]. Because electricity input costs comprise up to 70% of the Levelized Cost of Hydrogen (LCOH), achieving price parity requires a dramatic scale-up of low-cost, ultra-reliable renewable energy infrastructure. This review provides a comprehensive analysis of how scaling solar, wind, and hybrid RE platforms can optimize capacity utilization factors, lower levelized electricity costs, and establish GH_2 as a pillar of India's sustainable economy.

The Current Landscape of Green Hydrogen and Renewable Energy in India

1. Installed Capacity Metrics and Institutional Paradigms

India's renewable energy sector has experienced significant growth over the past decade, driven by aggressive public bidding protocols, land-bank allocations, and private capital inflows [5]. India's total non-fossil fuel installed electricity capacity reached substantial thresholds, placing the nation among the global leaders in total renewable energy installations. This extensive infrastructure ranks India fourth globally in terms of total renewable energy capacity.

Total Non-Fossil Fuel Capacity Framework (India)

Solar Power Infrastructure (Primary Contributor)
Wind Power Generation (Secondary Contributor)
Large Hydro and Pumped Storage
Bio-Energy & Nuclear Assets

This massive grid ecosystem forms the logistical baseline for the National Green Hydrogen Mission (NGHM), which mandates an annual production of 5 MMT of GH2 by 2030. Meeting this target requires an additional, dedicated installation of at least 125 GW of renewable energy capacity exclusively configured to power multi-megawatt electrolyzer stacks [6].

To bridge the near-term commercial financing gap, the central government has committed programmatic outlays under the Strategic Interventions for Green Hydrogen Transition (SIGHT) program [3]. This program allocates substantial funding for domestic electrolyzer manufacturing incentives and direct production subsidies. Competitive tranches executed by the Solar Energy Corporation of India (SECI) successfully allocated subsidies for green hydrogen and green ammonia production capacity, recording some of the lowest commercial green molecule delivery bids globally.

2. **Techno-Economic Dissection of Hydrogen Production Costs**

The financial profile of green hydrogen production is determined by the intersection of capital and operational components, formally calculated through the Levelized Cost of Hydrogen (LCOH) [2,7]. This is expressed through standard economic evaluations as a function of capital expenditures (CAPEX), operational expenditures (OPEX), and electricity procurement parameters over the lifespans of the infrastructure.

The primary sub-factors governing this formulation are:

Renewable Electricity (60%–70%): Solar/Wind tariffs, Inter-state transmission open-access charges, grid banking fees.

Electrolyzer CAPEX (20%–25%): Stack technology type (Alkaline vs. PEM), manufacturing scale, critical catalyst metals.

System OPEX & Water (5%–10%): Demineralization systems stack degradation retrofits, cooling utilities.

To achieve the targeted LCOH threshold of \$1.00 to \$1.50/kg, the cost of input renewable electricity must drop drastically, and stack capacity utilization factors must be maximized to reduce amortized capital expenses.

Renewable Energy Scaling as the Primary Cost Driver

1. **Impact of Co-located Solar and Wind Complementarities**

The primary challenge of utilizing solar or wind assets for water electrolysis is their inherent diurnal intermittency and seasonal volatility. A standalone solar PV plant operates at a low Capacity Utilization Factor (CUF), meaning an electrolyzer connected exclusively to a solar array remains idle for nearly 75% of the year. This low utilization sharply inflates the impact of amortized CAPEX on each kilogram of hydrogen produced.

To resolve this limitation, India is prioritizing the deployment of co-located solar-wind hybrid systems. Solar generation peaks during midday hours, whereas onshore and offshore wind resources generally strengthen during evening and night periods. Integrating these complementary profiles allows utility-scale hybrid configurations to achieve a continuous, stable CUF [4,5].

Solar Generation Profile: Peak: Midday Window.
Wind Generation Profile: Peak: Nocturnal Window.
Combined Hybrid Ecosystem: Stabilized CUF: 55%-65%.

By maintaining a steady electrical input to the electrolyzer stack, developers can maximize hydrogen output per megawatt of installed stack capacity, mitigating structural thermal stress on membranes and significantly extending the operational life of the system.

2. **Open-Access Regulations, Grid Transmission, and Banking Policies**

Because India's prime renewable energy zones (such as the high-solar deserts of Rajasthan and the wind corridors of Gujarat) are often located far from heavy industrial clusters, long-distance transmission infrastructure is vital. The central government's waiver of Inter-State Transmission System (ISTS) charges for green hydrogen production facilities commissioned before 2030 has removed a significant midstream cost barrier.

Furthermore, uniform green energy open-access rules allow GH_2 developers to bypass regional distribution monopolies and secure clean power directly from independent power producers. Electricity "banking" policies are equally critical. These rules permit developers to inject excess renewable power generated during peak windows into the national grid and draw down an equivalent volume during low-generation periods. However, regulatory friction persists because individual states enforce inconsistent monthly or annual banking limits and charge varying settlement fees. Standardizing interstate banking frameworks is essential to ensure long-term, predictable pricing models for green hydrogen.

Techno-Economic Evaluation of Electrolyzer Technologies

The choice of electrolyzer technology dictates the operational efficiency, water purity demands and capital footprint of a green hydrogen facility [8]. Three primary configurations dominate the current industrial landscape: Alkaline Electrolysis (AEL), Proton Exchange Membrane (PEM) Electrolysis and Solid Oxide Electrolysis Cells (SOEC) [7, 8, 9].

1. **Alkaline Electrolysis (AEL)**

Alkaline systems represent the most mature and economically accessible technology deployed in India. Utilizing a liquid potassium hydroxide (KOH) or sodium hydroxide (NaOH) electrolyte alongside non-noble catalysts (nickel and steel), AEL systems avoid dependencies on scarce precious metals.

Advantages: Lower stack CAPEX, extended commercial lifespans, and large-scale manufacturing baselines.

Limitations: Limited dynamic flexibility, making them less compatible with highly volatile, unbuffered renewable power feeds. They also exhibit lower operational current densities.

2. **Proton Exchange Membrane (PEM) Electrolysis**

PEM systems replace liquid electrolytes with a solid perfluorosulfonic acid membrane, utilizing noble metal catalysts including platinum at the cathode and iridium at the anode.

Advantages: High dynamic flexibility with rapid response times, allowing them to track the volatile output of wind and solar systems without needing upstream power-conditioning layers.

Limitations: Significantly higher capital costs and acute exposure to global supply chain disruptions for rare iridium and platinum resources.

3. **Solid Oxide Electrolysis Cells (SOEC)**

SOECs represent an emerging high-temperature technology that utilizes solid ceramic materials as the electrolyte layer.

Advantages: Exceptional electrical efficiency. When integrated with waste heat from heavy industrial plants like steel mills or oil refineries, the electrical energy required to split water drops significantly.

Limitations: High material degradation rates driven by thermal stress, high initial CAPEX, and a lack of manufacturing capacity at gigawatt scale.

Key Infrastructure and Environmental Challenges

1. **Water Resource Vulnerability and Demineralization Economics**

A critical environmental factor frequently overlooked in energy transition models is the intensive consumption of freshwater during electrolysis. The stoichiometric baseline requires approximately 9 liters of high-purity demineralized water to generate 1 kilogram of green hydrogen [7,8]. Accounting for operational cooling, purification flush cycles, and pretreatment backwashing, the practical consumption ratio escalates to 18 to 24 liters of raw freshwater per kilogram of hydrogen.

This creates a serious spatial contradiction: India's highest-yielding solar generation assets are located within hyper-arid zones like Western Rajasthan and Northern Gujarat, regions already suffering from acute, systemic groundwater depletion and water stress.

Water Scarcity Risk Interface: [Arid RE Zones (Rajasthan/Gujarat)] High Solar Yield ↔ Acute Water Deficit

To prevent competition with domestic and agricultural water supplies, India must evaluate the use of desalinated seawater or treated municipal wastewater for GH_2 projects. While seawater desalination adds a long-distance pipeline transport challenge, the economic impact of desalination processing itself is relatively low, contributing minimally to the final LCOH.

2. **Critical Mineral Bottlenecks and Supply Chain Security**

The rapid expansion of domestic electrolyzer manufacturing capacity, projected to surpass extensive thresholds by 2030, introduces significant mineral dependencies [6,9]. Alkaline systems require substantial volumes of specialized nickel, copper, and industrial steel. PEM systems rely heavily on platinum-group metals.

India lacks major domestic reserves of nickel and iridium, leaving its green energy transition exposed to international trade dependencies and price volatility. Mitigating this risk requires targeting public R&D investments toward developing catalyst materials that minimize or replace precious metals, alongside securing long-term bilateral mineral procurement agreements with resource-rich nations.

3. **Midstream Logistics: Storage, Transport, and Cluster Strategy**

Hydrogen possesses an exceptional gravimetric energy density but an extremely low volumetric density under ambient conditions. Compressing hydrogen to 350–700 bar or liquefying it at cryogenic temperatures requires substantial capital investment and consumes a significant percentage of the energy contained within the gas itself.

To minimize these transport inefficiencies, India is deploying a "Hydrogen Valley Innovation Cluster" (HVIC) strategy. These specialized zones co-locate renewable energy generation, water purification plants, and gigawatt-scale electrolyzer stacks directly adjacent to high-volume industrial consumers like fertilizer plants and refineries. This geographical clustering removes the need for long-distance midstream transport infrastructure, allowing green hydrogen to be delivered via localized, low-pressure micro-pipelines at minimal cost.

Strategic and Policy Recommendations for India

To successfully drive the market cost of green hydrogen down to competitive targets by 2030, India should implement a coordinated set of policy interventions:

Mandate Phased Green Hydrogen Consumption Blending: Introduce binding, escalating quotas requiring oil refineries and fertilizer plants to substitute a progressive percentage of their grey hydrogen consumption with green alternatives. This will generate a reliable domestic demand signal to attract private capital.

Standardize Inter-State Green Energy Banking Policies: Enforce a unified national framework for electricity banking with a guaranteed 30-day settlement window. This will eliminate regional regulatory risks and lower financing costs for developers.

Accelerate R&D for Next-Generation Electrolyzers: Provide direct fiscal grants to academic and industrial consortia focused on localized, low-iridium PEM stacks and high-efficiency, durable Solid Oxide systems.

Establish Dedicated Green Hydrogen Maritime Corridors: Accelerate the development of export infrastructure at key national ports to position India as a low-cost exporter of green ammonia to European and Asian markets.

Conclusion

Scaling renewable energy infrastructure is the foundational element required to unlock cost-effective green hydrogen production in India. By leveraging its exceptional solar and wind resources, India can systematically lower the levelized cost of clean electricity, reducing the primary cost component of the LCOH equation. Meeting the country's ambitious 2030 targets will require overcoming several key technical and structural challenges, including industrial-scale electrolyzer manufacturing, regional water resource constraints, critical mineral availability, and midstream transport efficiency. Through targeted policy frameworks like the National Green Hydrogen Mission, strategic investments in solar-wind hybrid technologies, and the implementation of localized Hydrogen Valley clusters, India can successfully bridge the price gap between grey and green molecules. Resolving these issues will protect the nation from volatile international fossil fuel markets, mitigate industrial carbon emissions, and establish India as a central hub in the emerging global green hydrogen economy.

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