Journal of Marketing & Social Research

ISSN (Online): 3008-0711

Volume: 03 | Issue 05 | 2026

Journal homepage: https://jmsr-online.com/

Research Article

An Empirical Study on the Role of Green Hydrogen in Decarbonizing the Power Sector: A Futuristic Indian Approach

Nitin Tejmal Kale1 and Dr. Amit Aggrawal[2]

[1]Research Scholar, Sandip University, Trimbak Road, Ta. Dist: Nashik, Maharashtra, 422213 India

[2]Professor, Marketing & Research Department, SOCMS, Sandip University, Trimbak Road, Ta. Dist: Nashik, Maharashtra, 422213 India

Received: 08/04/2026; Revision: 22/04/2026; Accepted: 02/05/2026; Published: 20/05/2026

Corresponding author: Nitin Tejmal Kale *(nitintkale1976@gmail.com)

Abstract: India is at a crucial juncture in its transition to sustainable energy. As the nation strives to meet its ambitious targets of achieving net-zero emissions by 2070 and complete energy independence by 2047, it faces a major challenge: balancing rapid economic growth with environmental responsibility[1]. This dual imperative requires the adoption of innovative energy solutions that can sustain industrial expansion while significantly reducing carbon footprints. Green hydrogen is emerging as more than just an alternative energy source; it is becoming a key component of India's strategy to cut carbon emissions and drive a cleaner, more resilient energy future. This research paper provides a comprehensive analysis of the vital role green hydrogen plays in transforming India's energy sector. It explores the current state of India's energy infrastructure, highlighting the limitations of conventional fossil fuel dependence and the pressing need for cleaner alternatives. The paper investigates the mechanisms of hydrogen-based energy storage, emphasizing how green hydrogen—produced through renewable energy-powered electrolysis—offers a versatile and sustainable energy carrier. It evaluates the government's National Green Hydrogen Mission (NGHM), a flagship initiative aimed at scaling production capacity and creating an enabling ecosystem. Additionally, the study identifies significant barriers to green hydrogen implementation, including technological challenges, infrastructure gaps, cost constraints, and policy hurdles. The findings suggest that green hydrogen, when combined with smart grid management systems and data-driven decision-making, can address three critical needs simultaneously: ensuring grid stability during the shift to renewable energy, decarbonizing hard-to-tackle sectors such as heavy industry and transportation, and enhancing the efficiency of electricity distribution. By enabling energy storage and flexible power generation, green hydrogen helps mitigate the intermittency issues associated with solar and wind power, thus supporting a more reliable and resilient grid. Furthermore, its application in sectors that are traditionally difficult to electrify positions green hydrogen as a transformative solution for comprehensive decarbonization. By 2030, India's National Green Hydrogen Mission aims to produce 5 million metric tons (MMT) annually, supported by 125 GW of dedicated renewable capacity, which will generate over 600,000 jobs and prevent 50 MMT of CO_2 emissions[1]. This ambitious target reflects the government's commitment to fostering a robust green hydrogen ecosystem that integrates production, storage, and end-use applications.

Keywords: Green Hydrogen, Renewable Energy Transition, National Green Hydrogen Mission (NGHM), Sustainable Energy Storage, Decarbonization of Industry and Transport.

INTRODUCTION

1.1 The Energy Paradox of Modern India

India's energy narrative is marked by a contradiction. On one side, the country has achieved significant strides in renewable energy, reaching a landmark in 2024 by exceeding 50% of its total installed electrical capacity from non-fossil fuel sources[2]. Solar and wind installations now span the regions from Rajasthan to Tamil Nadu, reflecting billions of dollars invested in clean energy. Conversely, India still heavily relies on coal for its primary electricity generation, with coal plants providing about 50% of the actual grid power, even though they account for only 46% of the installed capacity[3]. This contradiction arises from a basic physics issue: renewable energy sources are inconsistent. Solar panels generate electricity only during daylight, often with seasonal fluctuations, while wind turbines produce power irregularly. Although battery energy storage systems (BESS) have seen significant advancements, they are economically feasible only for short-term storage (4–6 h), which is inadequate for the seasonal energy imbalances typical of South Asian monsoon patterns[4]. In this context, green hydrogen completely changes the dynamics.

1.2 Understanding Green Hydrogen: From Concept to Reality

Green hydrogen production is founded on a simple yet effective concept: using renewable electricity to power water electrolysis. When an electric current is applied to purified water (H_2O), it separates into hydrogen gas (H_2) and oxygen (O_2). The key factor that sets "green" hydrogen apart from its environmentally harmful gray counterpart is the source of electricity used in this process[5]. Presently, about 95% of global hydrogen is "grey hydrogen," generated through steam methane reforming (SMR) of natural gas or coal gasification—methods that emit 9-12 tons of CO_2 for each ton of hydrogen produced[1]. In contrast, green hydrogen only emits water vapor, whether burned in turbines or used in fuel cells, fostering a truly

Name: Nitin Tejmal Kale
Email: nitintkale1976@gmail.com

circular energy economy[2].

The process can be conceptually illustrated as: $2H_2O$ + Renewable Electricity → $2H_2 + O_2$.

This holds significant potential for India, a country with some of the world's richest solar resources, boasting solar irradiance of over 5 kWh/m²/day in most regions [3]. By leveraging this resource for hydrogen production, India can effectively store solar energy in chemical bonds, releasing it as needed, whether for electricity generation during cloudy monsoon periods or for direct industrial use.

1.3 Why Green Hydrogen for India Now?

India's green hydrogen initiatives are strategically timed, driven by a combination of pressing needs and emerging opportunities:

Economic Vulnerability: With India importing around 85% of its oil and 40% of its natural gas, the country faces an annual import expense surpassing $120 billion[4]. Factors such as global geopolitical tensions, OPEC's production choices, and fluctuations in petrocurrency significantly affect India's macroeconomic stability. By producing green hydrogen domestically, India can significantly reduce this dependency[1].

Climate Commitments: Under the Paris Agreement, India's Nationally Determined Contribution (NDC) aims to cut the emissions intensity of its GDP by 45% by 2030, compared to 2005 levels[5]. The power sector, which accounts for about 42% of India's greenhouse gas emissions, is crucial for meeting these targets[3]. Grid transition complexity: As renewable energy's share exceeds 40% of total generation, maintaining grid stability becomes increasingly complex. Green hydrogen offers the long-duration energy storage solution necessary for a safe transition[4].

Industrial Decarbonization: The steel and cement industries consume 30% of India's industrial energy, mainly through coal-based thermal processes. Green hydrogen can replace these carbon-heavy heat sources directly[2].

Objectives of the study:

1) To analyze the current state and challenges of India's power sector with respect to decarbonization and the integration of green hydrogen as a sustainable energy solution.
2) To evaluate the role of green hydrogen in addressing grid stability, long-duration energy storage, and decarbonization of hard-to-abate industrial sectors in India.
3) To assess the implementation framework, policy initiatives, and economic viability of India's National Green Hydrogen Mission (NGHM) aimed at scaling green hydrogen production by 2030.
4) To identify key barriers such as technological, infrastructural, economic, and resource-related challenges hindering the widespread adoption of green hydrogen in India and propose strategic recommendations for overcoming them.

RESEARCH METHODOLOGY:

This research employs a comprehensive qualitative and quantitative approach based on secondary data analysis. It involves:

- Reviewing official government documents, policy frameworks, and mission reports related to the National Green Hydrogen Mission and renewable energy targets.
- Analyzing statistical data on India's current energy infrastructure, installed capacity, and emission profiles sourced from authoritative energy sector databases and publications.
- Examining technical literature on green hydrogen production, storage, and utilization technologies to understand efficiency, cost trajectories, and scalability.
- Conducting a comparative assessment of cost and environmental benefits between green hydrogen and conventional fossil fuel-based energy sources.
- Evaluating case studies and pilot projects within India's industrial and transportation sectors to highlight practical applications and challenges.
- Synthesizing macroeconomic and employment impact projections based on government and industry forecasts.
- Identifying gaps and constraints through critical analysis of infrastructure, water resource availability, and market readiness to inform strategic policy recommendations.

This mixed-method approach enables a holistic understanding of green hydrogen's potential and challenges in India's power sector decarbonization pathway.

2. India's Power Sector: The Decarbonization Challenge and Current Status

2.1 The Current Energy Landscape

India's power sector serves as a reflection of global energy challenges. As the world's third-largest energy consumer and the fourth-largest producer of electricity, India's installed capacity of over 400 GW caters to a population of 1.4 billion, characterized by significant disparities in consumption patterns[1]. While urban areas expect uninterrupted power supply, rural regions struggle with insufficient infrastructure[2].

By January 2026, the composition of India's installed capacity reveals a complex scenario.

Energy Source	Installed Capacity (GW)	Percentage of Total
Coal (Thermal)	180-190	46%
Renewable Energy (Solar + Wind)	140-150	35%

Hydroelectric	45-50	11%
Nuclear	6-7	2%
Natural Gas	20-25	5%
Biomass	10-12	3%

Table 1: India's Installed Power Generation Capacity (January 2026)

Nevertheless, the distribution of installed capacity conceals a deeper truth. When examining actual electricity production in GWh, it becomes evident that coal continues to play a leading role in providing baseload power. Despite the fact that non-fossil fuel capacity collectively surpasses 50%, coal still contributes to 48–52% of the electricity actually produced. This is largely due to the intermittent nature of renewable energy sources and the weather-dependent nature of hydroelectric power generation[3].

2.2 The Baseload Generation Paradox

Understanding the difference between installed capacity and actual generation capacity is essential for grasping the significance of green hydrogen. For instance, a 100 MW solar farm with a 20% capacity factor produces the same amount of electricity annually (around 175 GWh per year) as a 20 MW coal plant with a 90% capacity factor[4]. This is a key factor in shaping the grid management challenges faced by India.

Current data indicates:

- **Coal Generation:** 48-52% of total electricity supply, with 0.75 kg CO_2 emitted per kWh
- **Renewable Generation:** 12-15% of total electricity supply, virtually zero emissions
- **Hydroelectric Generation:** 11-13% of total electricity supply, seasonal variation ±15%
- **Gas/Other:** 8-10% of total electricity supply, variable emissions
- **Unmet Demand/Load Shedding:** 2-4%, particularly in rural areas[5]

2.3 The Emissions Burden

India's energy sector is responsible for emitting around 1.5–1.7 billion metric tons of CO_2 each year, accounting for roughly 40% of the country's total greenhouse gas emissions[1]. To meet the NDC goal of reducing emissions intensity by 45% by 2030, significant changes in the sector are necessary. Current trend analysis indicates that without structural changes, such as incorporating hydrogen, India could encounter the following issues:

Supply-Demand Imbalance: A predicted 15-20% deficit in peak demand capacity by 2030 if renewable energy is integrated without sufficient storage solutions[2].

Grid Instability: Frequency variations surpassing safe operational limits (±0.2 Hz from the nominal 50 Hz) occurring 10-15 times a year[3].

Stranded Coal Investments: ₹2-3 lakh crore in coal power plant investments becoming redundant before their economic lifespan ends[4].

Agricultural Impact: Inconsistent power supply affecting agricultural pump sets, impacting 70 million farmers across India[5]. Green hydrogen offers a direct solution to these problems.

3. The Mechanics: How Green Hydrogen Decarbonizes the Grid and Industrial Sectors

3.1 Long-Duration Energy Storage (LDES)

Green hydrogen plays a pivotal role in India's shift to renewable energy by addressing the timing mismatch between when renewable energy is produced and when it is needed[1]. Although battery energy storage systems have seen significant cost reductions (dropping from $1,100/kWh in 2010 to $130/kWh by 2025), they still face economic challenges for storage periods longer than 6-8 hours[2].

Green hydrogen offers a solution for storing energy over longer periods, particularly for seasonal needs. For instance, during the monsoon season from June to September, solar energy production decreases by 40% to 50% due to rain, while hydroelectric power increases. In contrast, from October to May, solar energy is plentiful, but hydroelectric resources are diminished. This six-month discrepancy highlights the necessity for seasonal energy storage[3].

The process is quite simple.

- **Charging Phase (summer months: May to September):**
  During the summer, particularly between 2 and 4 PM, surplus solar energy is utilized to operate electrolysers. These electrolysers transform water into hydrogen with an efficiency ranging from 70% to 86% in the current generation. The hydrogen is then compressed to pressures between 350 and 700 bar and stored in pressurized tanks, salt caverns, or depleted natural gas reservoirs. This storage system allows for loss-free retention over several months[4].
- **Discharge Phase (Winter months - October-April):**

In the winter, the stored hydrogen is converted back into electricity using fuel cells or modified combined-cycle gas turbines. The round-trip efficiency is between 30% and 50%, which is considered acceptable for seasonal storage when compared to the alternative of burning fossil fuels. The electricity produced is injected to align with demand patterns during periods of low renewable energy generation[5].

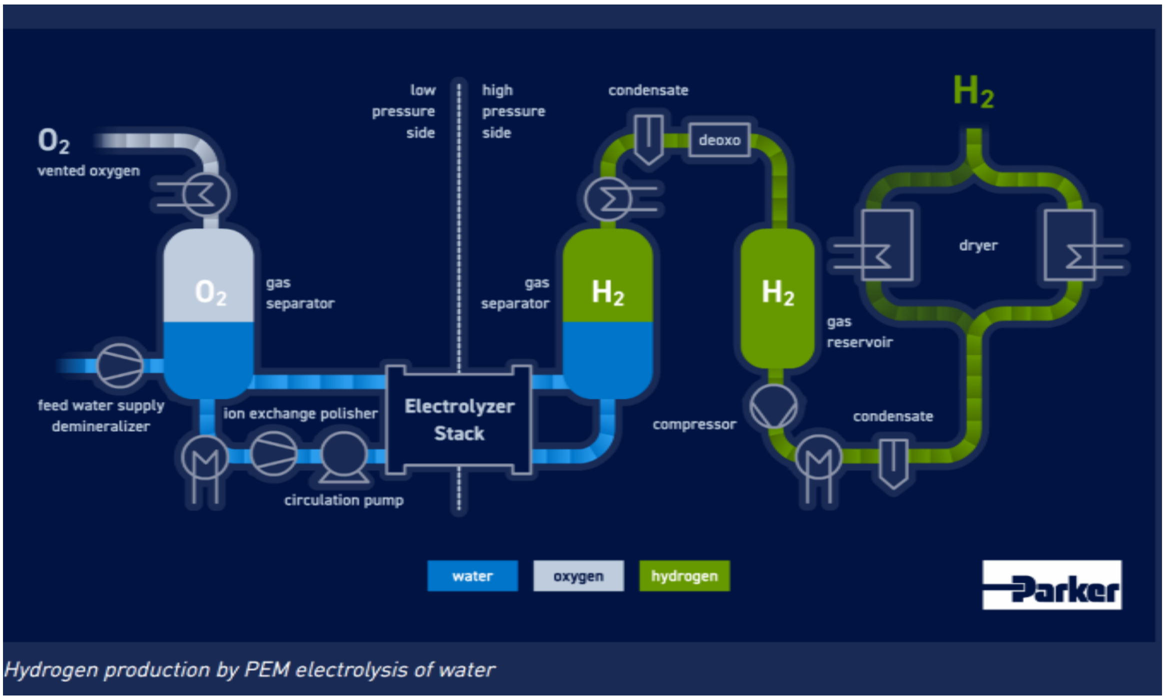

Figure 1: Cycle for Generating Green Hydrogen

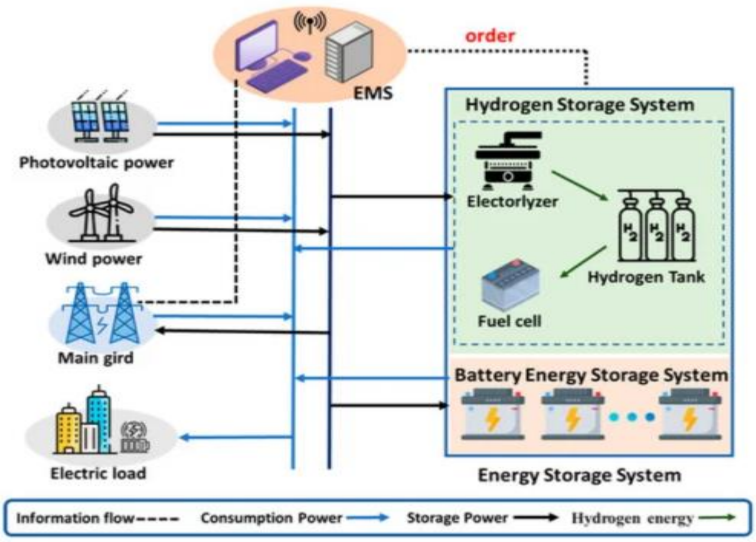

Figure 2: Green Hydrogen Energy Storage Cycle

3.2 Grid Balancing and Ancillary Services

Beyond its role in seasonal storage, green hydrogen offers immediate grid stabilization through the adaptability of electrolyzers[1]. Unlike power plants, which need 4–8 hours to start from a cold state, industrial electrolyzers can adjust their output in mere seconds to address grid frequency changes[2]. This introduces a new function where the electrolyzer serves as a responsive load absorber. When there is a sudden increase in renewable energy (such as when passing clouds cause rapid changes in solar irradiance), electrolyzers can increase hydrogen production within 30–60 seconds, using the surplus power and preventing grid frequency fluctuations[3]. Traditionally, this ancillary service relies on spinning reserves—gas plants operating at reduced capacity and burning fuel without producing electricity for sale. Green hydrogen converts these inefficiencies into stored energy[4].

India's current grid stability standards necessitate the following: Frequency Deviation Management, which involves keeping the grid frequency between 49.5 and 50.5 Hz with a tolerance of ±1%; Ramping Requirements, which entail accommodating power shifts of 1,000 to 2,000 MW per minute during the integration of renewable energy; and Reserve Capacity, which requires maintaining a spinning reserve of 15-20% to address unexpected outages[5]. Green hydrogen electrolyzers can meet 40–60% of the reserve capacity needs at a significantly lower cost than gas turbines, while also producing valuable fuel[1].

3.3 Decarbonizing Hard-to-Abate Industrial Sectors

Green hydrogen holds significant potential for transformation in industries where direct electrification is either technically unfeasible or economically impractical[1]. Steel Manufacturing: India annually produces over 100 million metric tons of steel, utilizing more than 80 MMT of coal, mainly coking coal. This results in the emission of around 250 MMT of CO_2 each year[2]. The hydrogen direct-reduction method, which is now commercially feasible, can completely replace coking coal:

Traditional blast furnace: $Fe_2O_3 + 3CO$ (from coke) $\rightarrow 2Fe + 3CO_2$
Hydrogen reduction: $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$

Companies like Steel Authority of India Limited (SAIL) are already experimenting with green hydrogen in pilot projects. A complete shift to this method could cut steel production emissions by 80%[3].

Cement production: The process of manufacturing cement contributes to 8% of the world's CO_2 emissions, amounting to 1.4 billion metric tons each year, with India accounting for more than 300 MMT[4]. Producing clinker requires thermal energy at temperatures ranging from 1,500 to 1,600 °C. Green hydrogen combustion meets this thermal demand without emitting carbon[5].

Green ammonia production: The synthesis of ammonia from hydrogen is crucial for producing fertilizers. At present, the global production of ammonia uses up 2% of the total fossil fuel energy supply[1]. In India, where over 35 million hectares are cultivated, there is a complete reliance on synthetic ammonia-based fertilizers. Producing green ammonia can help decarbonize agriculture while sustaining crop yields[2].

Heavy Transportation: Battery-electric vehicles encounter inherent challenges when it comes to applications that demand continuous high power for long periods.
Hydrogen fuel cells offer: Energy density: 120–140 MJ/kg (compared to 0.5-1 MJ/kg for lithium-ion batteries)
Refueling time: 3-5 minutes (as opposed to 30-60 minutes for fast-charging)
Operating range: 400-700 km per full tank Payload capacity: Comparable to diesel vehicles[3]
Hydrogen-powered vehicles present feasible decarbonization options for long-distance trucking, port activities, and freight corridors[4].

4. India's National Green Hydrogen Mission: Governance and Execution Framework

4.1 Mission Structure and Policy Framework

In January 2023, recognizing the crucial role of hydrogen, the Government of India launched the National Green Hydrogen Mission (NGHM) with an initial allocation of ₹ 19744 crore[1]. This initiative is among the most significant clean energy policies in the region, underscoring the government's commitment to fundamentally transforming the energy sector[2].
The NGHM comprises several integrated components.

4.1.1 SIGHT Programme (Strategic Interventions for Green Hydrogen Transition)

Allocation: ₹17,490 crore (88% of the total budget) The SIGHT initiative offers financial incentives in two key areas:
Support for Electrolyser Manufacturing: A Production Linked Incentive (PLI) scheme grants ₹4,000-4,500 per MW for electrolyser capacity produced domestically, with a goal of achieving 5-GW annual electrolyser production by 2030[3].
Incentives for Green Hydrogen Production: Performance-based incentives of ₹40-50/kg are provided for green hydrogen production, aiming to close the cost gap between green and grey hydrogen[4].
This dual-incentive approach simultaneously tackles supply-side (availability of electrolysers) and demand-side (feasibility of production) challenges[5].

4.1.2 Green Hydrogen Hubs Development

Allocation: ₹400 crore for 2023-2026 The mission focuses on identifying and developing "green hydrogen hubs," which are geographic clusters where hydrogen is produced, stored, distributed, and used within integrated ecosystems. The designated hub locations are:

Kandla Port (Gujarat): Utilizing the wind resources of the Gulf of Kutch and the existing petrochemical infrastructure
Paradip Port (Odisha): Capitalizing on the renewable capacity of the eastern region and port infrastructure for export
Tuticorin Port (Tamil Nadu): Establishing a southern hub with solar and marine resources
Vishakapatnam (Andhra Pradesh): An industrial cluster with potential for renewable integration
Hazira (Gujarat): A petrochemical complex transitioning into a hydrogen hub[1]

These hubs have a dual purpose: to cater to domestic industrial consumption and to export to regions lacking hydrogen, such as Japan, South Korea, and Europe[2].

4.1.3 Pilot Project Implementation

Allocation: ₹1,466 crore for strategic pilot initiatives, including

- Steel Sector Pilots: ₹455 crore dedicated to testing low-carbon steel production at SAIL's Durgapur and Rourkela facilities
- Mobility Pilots: ₹496 crore allocated for deploying hydrogen fuel cell vehicles in selected cities
- Shipping Pilot: ₹115 crore for demonstrating hydrogen-powered vessels in coastal operations
- Decentralized Energy: Pilot projects for off-grid hydrogen systems aimed at rural electrification[3]

4.2 Regulatory and Certification Framework

- In April 2025, India introduced the Green Hydrogen Certification Scheme of India (GHCI) to ensure investor confidence through standardized certification[1]. This initiative includes:
- Lifecycle Emissions Assessment: Certification mandates confirmation that hydrogen production emits less than 0.36 kg CO_2-eq per kg H_2, following lifecycle assessment methods aligned with ISO 14040/14044[2].
- Additionality Requirements: All renewable energy used for hydrogen production must be "additional," meaning it does not replace existing renewable sources, to guarantee authentic emissions reduction[3].
- Traceability Standards: A digital verification system allows for real-time monitoring from production to consumption, preventing greenwashing[4]. This certification framework is crucial for international trade, ensuring that Indian green hydrogen complies with the standards of importing countries, especially Japan and Korea, which have stringent hydrogen certification requirements[5].

4.3 Financing and Investment Mechanisms

- The initiative aims to generate over ₹8 lakh crore (around $100 billion) by 2030 through various strategies. Government Capital Investment: A direct allocation of ₹19,744 crore
- National Bank Financing: Concessional loans provided by NABARD and development finance institutions
- Green Bonds: An estimated ₹3-4 lakh crore in bonds for green hydrogen infrastructure Foreign
- Direct Investment: An expected $20-30 billion from countries lacking hydrogen, seeking long-term supply assurance Private Equity and Infrastructure Funds: Anticipated involvement in the development of hydrogen hubs[1]

DATA, PROJECTIONS, AND 2030 MILESTONES: QUANTIFYING TRANSFORMATION

5.1 Government Targets and Implementation Roadmap

The National Green Hydrogen Mission has established specific, measurable targets for 2030, representing a transformation at scale:

Parameter	2030 Target	Current Status (2025)
Annual Production Capacity	5 Million Metric Tonnes (MMT)	<0.05 MMT
Dedicated Renewable Capacity	125 GW	15-20 GW (pilot phase)
Electrolyser Manufacturing Capacity	5-7 GW annually	0.1-0.2 GW (pilot)
Investment Mobilized	₹8 Lakh Crore	₹2,000-2,500 Cr approved
Employment Generated	600,000+ new jobs	10,000-15,000 (pilot)
Fossil Fuel Import Reduction	₹1 Lakh Crore savings	Baseline
CO_2 Emission Abatement	50 Million Metric Tonnes/year	Target trajectory
International Export Capacity	1-1.5 MMT/year	Pilot shipments (2025)

Table 2: National Green Hydrogen Mission: 2030 Targets and Progress Assessment (Source: Ministry of New and Renewable Energy, Government of India, March 2026)

5.2 Cost Trajectory and Economic Viability

Lowering costs is a key factor in assessing the market viability of green hydrogen. The current study highlights encouraging patterns:

Production costs projected for 2025:

1) Electrolyser capital expenditure (CAPEX) constitutes 40-60% of the levelized cost of hydrogen.
2) Electricity costs represent 30-50% of the overall production expense, significantly affected by renewable tariffs.
3) Globally, the cost of producing green hydrogen is ₹180-250/kg ($2.20-3.00/kg), whereas in India, it ranges from ₹200-280/kg.
4) By comparison, the cost of producing grey hydrogen is between ₹80-120/kg ($1.00-1.50/kg).

Expected cost reductions by 2030 include:

1) A 70% reduction in electrolyser costs, decreasing from the current $800-1,200/kW to $240-360/kW.
2) Renewable electricity costs are anticipated to drop to ₹2.00-2.50/kWh for dedicated solar-wind capacity.
3) The goal for green hydrogen production costs is set at under ₹100/kg ($1.20-1.50/kg)[1].

Reaching cost parity with fossil-based alternatives is essential for the voluntary industrial adoption of hydrogen without policy mandates[2].

The path to cost reduction is shaped by:

1) Advances in electrolyser technology, with efficiency expected to improve from the current 70-86% to 90-94% by 2030.
2) Manufacturing scale, where each doubling of cumulative production volume results in a 25-30% cost reduction.
3) Innovations in materials, such as developing cheaper catalysts to reduce reliance on precious metals like platinum and iridium.

The ongoing decline in renewable energy costs, with solar already priced at $0.02-0.03/kWh for utility-scale projects in India, and offshore wind[3].

5.3 Employment and Socioeconomic Impact

The NGHM anticipates the creation of over 600,000 new jobs by 2030, primarily in the sectors of manufacturing, installation, operation, and maintenance[1]. These roles encompass a range of skill levels: High-skill positions include electrolyser design engineers, hydrogen fuel cell experts, and grid management specialists. Mid-skill roles involve manufacturing technicians, pipeline installation workers, and fuel cell system maintenance personnel. Support roles cover logistics, supply chain management, and safety and quality assurance[2]. The geographical spread of these jobs is crucial for regional fairness. Hydrogen hub sites in Gujarat, Odisha, Tamil Nadu, and Andhra Pradesh are emerging as industrial clusters that enhance employment through supply chain development[3].

5.4 Import Reduction and Macroeconomic Benefit

The mission's goal of achieving ₹1 lakh crore in annual savings from fossil fuel imports signifies a significant macroeconomic advantage. Currently, petroleum imports exceed 200 million tons annually, costing approximately ₹12-14 lakh crore. By 2030, green hydrogen could potentially replace 10-15% of petroleum needs, leading to savings of ₹1-1.5 lakh crore. This would positively affect foreign exchange by decreasing currency outflows, thereby facilitating domestic capital investments. Additionally, it would enhance energy security by reducing reliance on suppliers from geopolitically unstable regions[1].

6. Roadblocks and Challenges:

Despite its compelling benefits, significant barriers require urgent attention to realize the vision of NGHM.

6.1 The Economics Challenge: Cost Competitiveness and Market Readiness

The most fundamental barrier remains economic viability. Although cost reduction trajectories appear promising, several headwinds persist[1]:

Electrolyzer technology costs:

The capital expenditure for current electrolyzers is between ₹ 40 and ₹ 60 lakh per megawatt of installed capacity. To reach the cost goals of ₹15-20 lakh per megawatt by 2030, the following are necessary: expanding to an annual manufacturing capacity of over 5 gigawatts (the current global capacity is 2-3 gigawatts), standardizing technology to enable efficient batch production, and establishing domestic supply chains for essential components like membranes, catalysts, and balance-of-system[2]. Without government support mechanisms such as the PLI scheme, private investors are hesitant to invest in electrolyzer manufacturing, as alternative investments in solar and wind systems present lower risks and proven returns[3].

The cost of electricity for producing hydrogen: Green hydrogen becomes economically feasible only when powered by renewable electricity costing less than ₹2.50 per kWh. Currently, renewable electricity costs in most areas range from ₹2.50 to ₹3.50 per kWh. Achieving costs below ₹2.00 per kWh requires: the deployment of ultra-mega renewable parks (5-10 gigawatt scale) to achieve economies of scale, long-term power purchase agreements (PPAs) to ensure cost certainty, and the development of transmission infrastructure to lower connection costs[4].

Competitive Pressures: International competition from regions with superior renewable resources, such as the Middle East, North Africa, and Australia, poses long-term challenges. Saudi Arabia's Green Hydrogen Program aims to achieve production costs of ₹ 0.50–0.70 per kg by 2030, leveraging its abundant solar resources[5].

6.2 Infrastructure and Logistics Challenges

Hydrogen's physical properties create substantial infrastructure requirements[1]:

Storage Infrastructure:

Hydrogen presents several distinct storage challenges. It necessitates pressurization between 350 and 700 bar or cryogenic cooling at -253°C. Its high flammability demands the use of specialized containment materials. To store the same amount of energy as gasoline, hydrogen requires about 20 to 30 times more volume. Currently, India does not have geological salt caverns suitable for large-scale underground storage[2].

Transportation and Distribution Unlike traditional fuels, distributing hydrogen involves the need for new high-pressure pipelines, costing ₹1-1.5 crore per km, compared to ₹50-100 lakh/km for natural gas. Export-quality green hydrogen requires specialized tanker vessels. Cryogenic liquefaction facilities, which cool hydrogen to -253°C, consume 20-30% of its energy[3].

The existing infrastructure gap necessitates the construction of over 500 km of dedicated hydrogen pipelines by 2030, with an estimated capital investment of ₹5000–7500 crore[4].

6.3 Water Scarcity: The Hidden Vulnerability

Perhaps the most critical but underappreciated challenge is water intensity[1].

Water Consumption:

Producing hydrogen through electrolysis necessitates about 9 liters of deionized water for every kilogram of hydrogen generated[2]. To meet India's 2030 goal of producing 5 million metric tons annually, this translates to roughly 45 billion liters each year, comparable to 18,000 Olympic-sized swimming pools[3].

In a country facing water scarcity, where: 80% of surface water is available during the 4-month monsoon season 60% of aquifers are overexploited Agricultural water needs are expected to rise by 20-25% by 2030 Urban and industrial water demands are intensifying[4] The development of green hydrogen must be strategically located to prevent new water shortages.

The approach includes: Incorporating desalination facilities at coastal hydrogen production sites Using treated wastewater from municipal treatment facilities Implementing water recycling within electrolyzer systems (up to 30% water recycling is possible) Focusing on developing hydrogen hubs in areas with sufficient renewable energy-powered desalination[5]

CONCLUSION:

India's shift towards sustainable energy is one of the most significant challenges of the 21st century. The country faces the task of achieving three historically conflicting goals: delivering consistent electricity to 1.4 billion citizens, fostering swift economic development, and preventing severe climate change. Green hydrogen, when combined with smart distribution systems and cutting-edge analytics, offers a revolutionary approach to meeting these objectives.

The scientific basis is clear: burning hydrogen results in only water vapor; electrolysis is a well-established, commercially available technology; and renewable energy sources are becoming more plentiful and cost-effective. The economic outlook is promising, with potential cost reductions of 60–70% by 2030 due to scaling and technological progress.

The policy agenda is bold, with the National Green Hydrogen Mission involving an initial investment of ₹ 19744 crore and the development of a comprehensive ecosystem. However, success is not guaranteed. Key challenges, such as the capacity for electrolyzer production, hydrogen infrastructure, water availability, and the complexity of grid integration, demand innovative solutions and ongoing dedication.

This research suggests that the key lies in combining two strategies:
Firstly, boost the domestic production of electrolyzers with the help of PLI support, aiming to lower capital expenses from the current ₹ 40–60 lakh/MW to a target of ₹ 15–20 lakh/MW by 2030. Secondly, introduce progressive blending mandates specific to each sector and implement carbon pricing strategies to ensure that the demand for hydrogen grows in tandem with production capabilities, thereby minimizing risks for private investors.

For India, green hydrogen signifies more than just a shift in energy sources; it embodies energy independence. A country that can generate its own high-energy-density fuel from local renewable resources fundamentally alters its geopolitical stance, liberating economic resources currently allocated to oil imports for domestic investments. By 2030, if India realizes this vision, the country will achieve the following: Reduce fossil fuel imports by ₹1 lakh crore annually, create 600,000 new skilled jobs, prevent 50 MMT of CO_2 emissions each year, establish itself as the world's third-largest hydrogen producer, and lay the groundwork for reaching Net Zero by 2070. The opportunity is evident. The moment is ripe. The mechanisms for execution are in place. What is needed now is the political determination, ongoing investment, and technological discipline to turn this vision into reality.

REFERENCES

1. Ministry of New and Renewable Energy (MNRE), Government of India, 2023 (2023). *National Green Hydrogen Mission: Detailed Framework Document*. https://nghm.mnre.gov.in
2. Press Information Bureau (PIB). (2025). *Unlocking India's Green Hydrogen Production Potential: Strategic Initiatives and Ecosystem Development*. Government of India.
3. Council on Energy, Environment, and Water (CEEW). (2024). *Assessing the Impact of Green Hydrogen Production on India's Power System: Technical and Economic Analysis*. CEEW Analysis Report.
4. International Energy Agency (IEA). (2025). *Global Hydrogen Review 2025: Accelerating Clean Hydrogen Deployment*. International Energy Agency Publications.
5. TERI (The Energy and Resources Institute). (2024). *Roadmap to India's 2030 Decarbonization Target: Power Sector Transition Pathways*. TERI Research Report.
6. Ember Global. (2024). *Green Electrification Can Unlock Clean Energy Gains for Indian Industries: Sectoral Analysis and Recommendations*. Ember Global Report.
7. Rocky Mountain Institute (RMI). (2025). *Green Hydrogen Production Pathways for India: Technology Selection and Deployment Strategy*. RMI South Asia Research.
8. World Energy Council. (2023). *World Energy Outlook 2023: India's Renewable Energy Integration Challenges*. WEC Publications.
9. National Hydrogen and Fuel Cell Technology Research, Development and Demonstration Program (US Department of Energy). (2024). *Hydrogen Production, Storage, and Utilization: Technical Progress and Emerging Challenges*. DOE Report.
10. Investindia. (2025). *India's Green Hydrogen Rise: Investment Opportunities and Policy Incentives for 2025-2030*. Investindia Market Analysis.
11. Montel Energy. (2026). *Hydrogen Production Cost Trends 2025-2030: Electrolyser Technology Advances and Market Outlook*. Montel Energy Analysis.
12. Siqens Research. (2025). *Energy Density*

Comparison: Hydrogen versus Battery Storage Technologies for Long-Duration Applications. Siqens Technical Report.

13. IRENA (International Renewable Energy Agency). (2024). *Renewable Energy Integration and Green Hydrogen: A Pathway to Net Zero*. IRENA Strategic Report.
14. Solartechonline. (2026). *Hydrogen Electrolysis: Complete Guide to Technologies, Cost Dynamics, and Market Projections*. Technical White Paper.
15. Central Electricity Authority (CEA), India. (2025). *Draft National Electricity Plan 2025-2030: Renewable Integration and Hydrogen Transition Strategy*. CEA Government Publication.