Green Hydrogen Reality Check 2025

White Paper

Prepared by

IIT Bombay Research Hub for Green Energy and Sustainability (GESH IITB)

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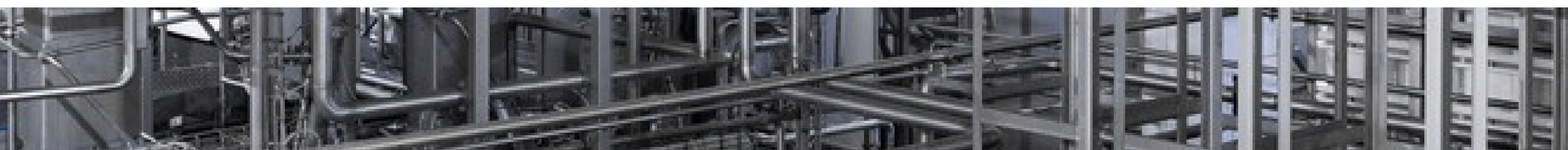


01 Introduction

1.1 About Green Hydrogen Reality Check 2025

The "Green Hydrogen Reality Check" conference, held at VMCC, IIT Bombay from February 20th to 21st, 2025, organized by the IIT Bombay Research Hub for Green Energy and Sustainability (GESH IITB) and co-organized by HSBC Bank, addressed the critical need to bridge the gap between India's ambitious green hydrogen targets and their practical implementation. Convened by Prof. Subramaniam Chandramouli and Dr. Anuradda Ganesh and supported by HSBC, the event brought together policymakers, industry leaders, and innovators to critically evaluate the progress in the nation's green hydrogen sector. Participants focused on identifying the hurdles impeding advancements, particularly in green financing, governance, and policy frameworks. The conference aimed to chart actionable pathways, fostering stakeholder collaboration to accelerate the development of a robust green hydrogen ecosystem and translate theoretical visions into concrete, achievable plans, with the outcomes documented in this whitepaper.

1.2 Background

The Government of India has set an ambitious target for green hydrogen as part of its broader energy transition strategy. The National Green Hydrogen Mission, launched in 2023, aims to position India as a global hub for green hydrogen production, with a goal of achieving 5 million metric tons (MMT) of annual production capacity by 2030. This initiative aligns with India's commitments under the Paris Agreement and its long-term objective of achieving net-zero emissions by 2070.
However, while the vision is clear, achieving these targets requires critically evaluating existing challenges, policy mechanisms, and industry readiness. The national and state-level policy initiatives are described in Annexure A.

A reality check is necessary to bridge the gap between vision and actual progress. The absence of clearly defined parameters to measure the success of green hydrogen initiatives in India creates a significant challenge. Several pathways exist for the attainment of government targets. For example, converting grey hydrogen production to green may offer a faster route to emission reductions by leveraging existing industrial demand and infrastructure. In contrast, creating new green hydrogen capacity could enable greater innovation, scalability, and long-term energy security. Each approach carries distinct policy, economic, and infrastructural implications.

To make informed decisions, it is crucial to establish well-defined benchmarks and performance indicators that can track progress against India's green hydrogen targets. These indicators should encompass production capacity, cost reductions, supply chain development, and integration with end-use sectors such as refining, fertilizer manufacture, steelmaking, and mobility. This white paper aims to provide a structured assessment of India's green hydrogen trajectory, identifying policy, infrastructure, and technology gaps while recommending a potential course of action to accelerate deployment.

1.3 Purpose of Reality Check

Achieving the 5 MMT annual production of green hydrogen requires accelerating the addition of renewable capacity. The present green hydrogen production capacity is around 175 tonnes per annum, indicating an unprecedented growth rate requirement in the coming years, as shown in Figure 1 (Press Information Bureau, 2025b). Based on the projected growth trajectory depicted in the graph, achieving the stated targets necessitates a significant and potentially challenging acceleration. Hence, establishing a clear and detailed roadmap underpinned by measurable annual milestones is critical under present circumstances. Without such a structured framework and a demonstrably steeper growth curve than previously observed, realizing the stated objectives remains highly uncertain.

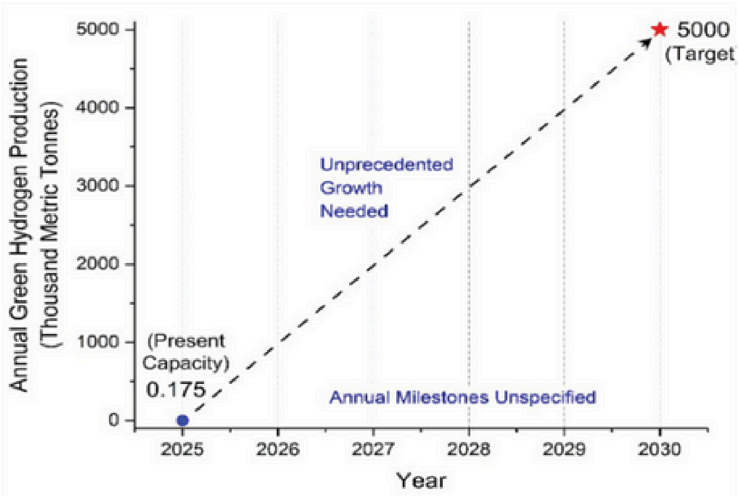


Figure1: India's Current and Forecasted Green Hydrogen Production Capacity

To meet the targeted green hydrogen production's electricity demands, the government anticipates an additional renewable energy capacity of approximately 125 GW (Press Information Bureau, 2025a). However, our analysis of various source mix scenarios, as illustrated in Figure 2, indicates that dedicated solar photovoltaic (PV) capacity for hydrogen production of up to 168 GW or wind capacity of up to 130 GW may be required by 2030. The significant gap between the existing capacity of solar PV and wind power and the capacity required for green hydrogen production, as shown in Figure 2, underscores the necessity of expanding solar and wind power capacity to meet the country's overall electricity demand. These estimations are predicted on average capacity utilization factors of 17% for solar PV and 22% for wind power, respectively. It is important to note that these initial calculations do not account for the temporal and spatial variability inherent in renewable energy generation, factors that could further influence the required capacity.

While India's ambitious green hydrogen targets are theoretically attainable, underpinned by Central Electricity Authority (CEA) projections for planned solar photovoltaic (PV) and overall renewable energy capacity additions, the current pace of deployment reveals critical discrepancies. Specifically, the CEA's 'Report on Optimal Generation Capacity Mix for 2029-30' estimates solar PV and wind capacity additions to approximately 270 GW and 99 GW, respectively (Central Electricity Authority, 2023). This suggests a potential surplus in solar PV capacity relative to the green hydrogen demand but a notable shortfall in wind power generation.

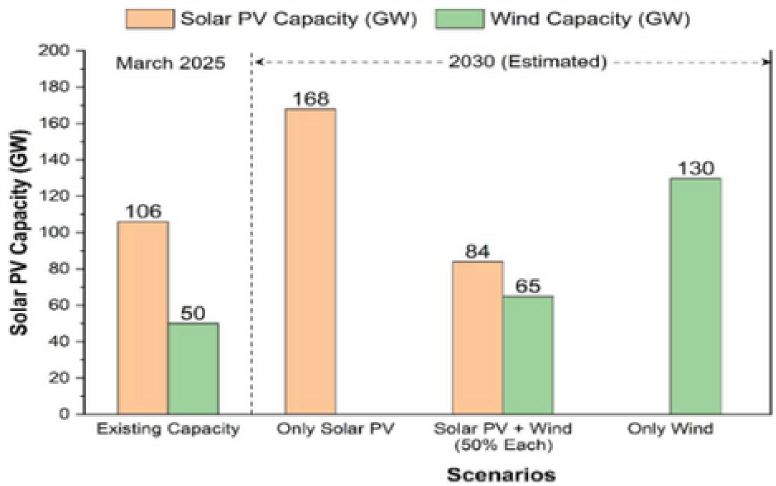


Figure 2 : Renewable Capacity Requirements Under Various Scenarios for India's 2030 Green Hydrogen Target. Authors' Estimates. Date source for existing capacity: (Ministry of New & Renewable Energy, 2025

Consequently, a balanced mix of renewable energy is required to ensure a firm and dispatchable electricity supply for future green hydrogen production. However, these targets may remain aspirational without a clear, actionable roadmap and measurable yearly milestones in each sector. Assuming a theoretical 100% load factor, the electrolyzer capacity required to meet the 5 MMT green hydrogen production target by 2030 is estimated to be 28.5 GW. However, the load factor of electrolyzers is highly dependent on the intermittent availability of renewable electricity and the fluctuating demand for hydrogen, invariably leading to a reduction in operational uptime and consequently necessitating a significantly larger installed electrolyzer capacity.

Today, India has a nascent electrolyzer capacity of less than 1 GW, with negligible commercial-scale green hydrogen production. While the government has approved projects for 3 GW of annual electrolyzer manufacturing capacity, achieving the ambitious 5 MMT production target within the next five years demands an unprecedented multi-fold scale-up of green hydrogen production, requiring a substantially steeper annualized growth rate in both electrolyzer deployment and green hydrogen output (Press Information Bureau, 2025a).

Drawing from the preceding analysis of renewable energy capacity projections, electrolyzer deployment status, and the ambitious green hydrogen targets, the purpose of this reality check becomes starkly apparent. The envisioned green hydrogen transition may remain an aspirational objective rather than a practical outcome if clear roadmaps are not established on time, measurable annual milestones are not set, and sustained momentum across all sectors is not maintained.

1.4 Objectives

This white paper details the developmental landscape of India's green hydrogen (GH_2) trajectory as of 2025, assessing the present environment regarding policy frameworks, industry readiness, technological advancements, and financial structures. While India has set ambitious targets, translating these commitments into tangible progress requires addressing critical bottlenecks and aligning key stakeholders. This white paper aims to provide a structured roadmap for accelerating India's green hydrogen transition, ensuring that set targets translate into measurable and sustainable progress. To enable the same, the following elements were studied and assessed:

Understanding the policy framework and recommendations for mitigating implementation bottlenecks
A well-defined and adaptive policy framework is essential to facilitate green hydrogen deployment. This paper aims to analyze existing regulations, identify gaps, and recommend policy interventions to streamline implementation, ensuring a stable and predictable environment for industry stakeholders. Assessing the current industry readiness and technology development: Scaling up green hydrogen production requires robust industrial participation and technological preparedness. The paper evaluates the current state of industry readiness, including production capabilities, supply chain constraints, and emerging technologies, while proposing strategies to strengthen domestic manufacturing and infrastructure.

Identifying the financing challenges and recommendations for accelerating investment trends
The financial viability of green hydrogen projects remains a key concern. This white paper examines existing financing mechanisms and risk mitigation strategies, offering insights into how India can attract private and institutional capital to accelerate deployment.

Exploring and expanding sectoral applications while reducing adoption barriers
Green hydrogen has the potential to decarbonize multiple sectors, including fine chemicals, refining, steelmaking, ammonia production, and mobility. However, sectoral adoption faces significant technical and economic barriers. This paper addresses the challenges hindering large-scale commercialization.

Strengthening research, innovation, and industry-academia collaboration
Advancing green hydrogen technology and ensuring its long-term viability depends on a strong research and innovation ecosystem. This paper highlights the role of R&D, industry-academia partnerships, and knowledge-sharing platforms in fostering innovation, reducing costs, and driving competitiveness in the global hydrogen economy, focusing on the challenges and opportunities of industry-academia collaboration in the Indian context.

02 Current Technologies & Industry Readiness

A holistic sectoral roadmap is necessary to drive systematic growth across industries. The first step in this direction would be to assess the present capability and future preparedness of the technology and domestic industry.

Hydrogen as a Commodity Business

The conceptualization of hydrogen projects as commodity businesses rather than purely infrastructure enterprises is critical for understanding the evolving hydrogen economy. This distinction has important implications for how technology development, industry readiness, and investment strategies are structured.

Hydrogen projects can be assessed as commodity rather than infrastructure projects, competitive pricing, and active participation in domestic and international trading markets. Hydrogen, like oil, natural gas, or metals, would be treated as a tradable product, emphasizing production optimization, supply chain efficiency, market pricing mechanisms, and resilience against volatility in global demand and supply. In contrast, an infrastructure-centered hydrogen business would prioritize constructing and operating physical assets—such as pipelines, storage terminals, electrolyzer parks, and refueling stations—with capital-intensive models that yield returns over longer investment horizons.

Understanding hydrogen as a commodity fundamentally shifts the focus of technology and industry readiness efforts. It requires accelerating advancements in production technologies (e.g., electrolyzer efficiency, scalable green hydrogen generation), developing flexible storage and transportation solutions, and establishing market-trading platforms that can handle price discovery, contracts, and supply guarantees. Readiness, therefore, is not limited to infrastructure deployment but also encompasses the technological capability to produce cost-competitive hydrogen at scale, the logistics capacity to deliver hydrogen flexibly, and the market frameworks that allow hydrogen to be bought and sold efficiently.

Treating hydrogen as a tradable product is particularly important for India as it builds its hydrogen ecosystem. Achieving cost competitiveness (targeting around \$1–\$2/kg by 2030, depending on policy support and renewable energy integration, as per the Ministry of New and Renewable Energy estimates) is essential for hydrogen to compete with grey hydrogen and fossil fuels. Consequently, technology standardization, industrial scale-up, and commodity trading readiness must be integral parts of India's hydrogen development strategy. Treating hydrogen as a commodity business ensures that the ecosystem evolves with a focus on market viability, rapid scalability, and integration into global trade flows—key components of true industry and technology readiness.

Focus on Translational Indigenous Research

Despite having strong research potential, the transition from pilot projects (Technology Readiness Levels 4–7) to large-scale commercial deployment in India remains slow. A well-structured, long-term strategy is essential to ensure India does not fall behind in this emerging sector. The country must take proactive steps before the technology becomes profitable, as seen in past industrial transformations - such as India's efforts in building an internal combustion engine (ICE) automobile sector and China's strategic push for electric vehicles (EVs).

Role of MSMEs in Developing Domestic Supply-Chain

Micro, Small, and Medium Enterprises (MSMEs) are crucial in building a robust domestic supply chain for various sectors in India, including automotive and auto components, textiles and apparel, electrical equipment, food processing, and agro-based industries. MSMEs can be incentivized to manufacture components and provide services that enable hydrogen production, storage, distribution, and utilization. Their participation enhances innovation, cost efficiency, and localization, making the green hydrogen sector more resilient and competitive. The ongoing Production-Linked Incentive (PLI) scheme can be extended to MSMEs to drive value addition and enhance their role in the green hydrogen economy.

In addition to the overarching challenges discussed above, specific issues arising at various stages of the hydrogen supply chain are examined in detail in the following subsections.

2.1 Production

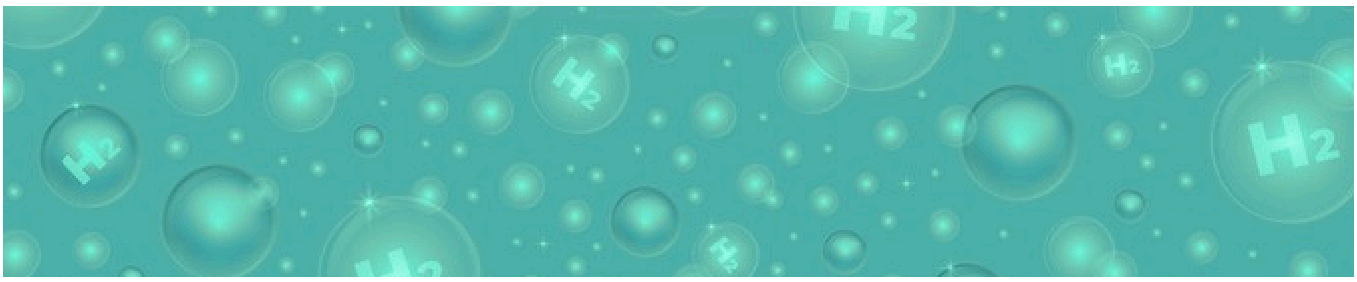
Hydrogen rarely exists in its free molecular form (H_2) in nature and must be extracted from compounds such as water (H_2O) or methane (CH_4). It can be obtained from fossil fuels, biomass, or through electrolysis using renewable energy. Natural gas is the dominant source of hydrogen production, accounting for approximately three-quarters of the total dedicated global hydrogen output, which stands at around 70 million tonnes per year. However, when hydrogen is produced using renewable energy, it is classified as Green Hydrogen. Key technologies for green hydrogen production include electrolysis and biomass gasification.

Electrolyzer-Based Production

Electrolysis is a widely adopted method for green hydrogen production, involving splitting water into hydrogen and oxygen using electricity. The global Electrolyzer manufacturing landscape is currently led by countries such as China, the United States, and Europe, with significant production capacities and technological advancements. The global commercial Electrolyzer manufacturing capacity is estimated to be only about 2-4 GW/annum. During the past 3 years, various national governments and industrial organizations have announced deployment goals totaling over 200 GW Electrolyzer capacity by 2030.

International benchmarks for electrolyzer efficiency are set by agencies like the IEA, IRENA, and the U.S. Department of Energy (DOE) (International Energy Agency, 2023). Efficiency is typically measured using hydrogen's Higher Heating Value (HHV). Alkaline electrolyzers operate at ~60–70% HHV efficiency, PEM electrolyzers at ~55–65%, and Solid Oxide Electrolyzer Cells (SOECs) can exceed 80% but remain primarily in R&D. The U.S. DOE targets 77% HHV efficiency by 2030. While India does not yet have formal national standards, efforts under the National Green Hydrogen Mission aim to align domestic benchmarks with these international norms.

India's domestic Electrolyzer manufacturing is still at a nascent stage. According to data from the Ministry of New and Renewable Energy (MNRE) and the National Green Hydrogen Mission (NGHM) portal, India has ambitious plans to scale up its Electrolyzer manufacturing capabilities. The SIGHT scheme under the NGHM has incentivized 3 GW of Electrolyzer manufacturing capacity within the country. The SIGHT scheme aims to de-risk first movers and provide viability support for early entrants in the green hydrogen sector. However, it should emphasize lowering reliance on imported electrolyzers.



Moreover, India should look beyond the assembly of imported components and focus on establishing an end-to-end domestic supply chain for electrolyzers by mitigating challenges associated with technical complexity and expertise, material availability, quality control standardization, and economies of scale and cost competitiveness. The essential electrolyzer components, such as membranes, catalysts, and bipolar plates, are currently sourced internationally.

Challenges to scaling electrolyzer production include the lack of standardized regulations, insufficient funding for large-scale demonstration projects, and the absence of efficiency benchmarks tailored to India's renewable energy landscape. International frameworks such as ISO 22734, IEC 62282-3, CertifHy (EU), and EU Renewable Energy Directive (RED II) offer valuable guidance for developing standardized electrolyzer safety, performance, and certification regulations. In the case of solar photovoltaics (PV), efficiency improvements have driven cost reductions. A similar approach is needed for hydrogen production, focusing on enhancing electrolyzer efficiency, reducing energy consumption per kilogram of hydrogen produced, and optimizing operational durability.

Bio-Based Hydrogen Production

Biohydrogen production methods, such as biomass gasification and microbial fermentation, are currently in India's research and development phase and have not yet achieved commercial viability or scalability. Therefore, policymakers and industry stakeholders need to adopt a pragmatic approach, allowing bio-hydrogen technologies to prove their economic and technical feasibility rather than assuming their viability.

Feedstock Challenges

Biomass-based hydrogen production faces a distinct set of technical and logistical constraints when compared to electrolysis-based methods. The Table 1 compares key parameters across both pathways to highlight efficiency, scalability, and operational feasibility differences.

Table 1 Comparison of Biomass-Based and Electrolysis-Based Hydrogen Production Pathways: Key Parameters, Performance Metrics, and Cost Considerations

Parameter	Biomass Gasification	Electrolysis (Water Splitting)
Feedstock Availability	Seasonal, geographically variable	Abundant (water); requires renewable electricity
Hydrogen Yield	~10–12 Nm^3/kg of dry biomass (0.9–1.1 kg H_2/100 kg biomass)	~55–65 kWh/kg H_2 produced (typical electrolysis efficiency 60–70%)
Energy Efficiency	~30–40%	~60–70% (PEM); up to 80% (ALK under ideal conditions)
Logistics Cost	₹2.5–₹3.5 per tonne per km (for biomass transport)	Minimal; electricity is grid-delivered
Feedstock Collection & Handling	Complex supply chain, decentralized sources	Centralized and predictable (electricity and water)
Capex/Unit	Lower capex, but highly site-dependent	Higher capex; cost of electrolyzer ~$500–1,000/kW

Parameter	Biomass Gasification	Electrolysis (Water Splitting)
GHG Emissions	It can be low if biomass is sustainably sourced; risk of methane/CO if incomplete gasification.	Near-zero if powered by renewable electricity
Scalability	Limited by biomass availability and collection radius (~50 km economic transport radius)	High scalability with access to VRE and water
Technology Maturity	TRL 5–6 (pilot to early demonstration)	TRL 8–9 (commercial-scale deployment in progress)

The experience of 2G bioethanol initiatives in India offers relevant insights for bio-hydrogen production. Challenges encountered in biomass aggregation, feedstock variability, and viability of long-distance transport significantly affected 2G ethanol commercialization. Similar risks may likely manifest in biomass-based hydrogen projects unless corrective measures are integrated early—such as feedstock supply assurance contracts, decentralized pre-processing centers, and viability gap funding. These lessons reinforce the need for location-specific planning and bundling of small-scale bio-H_2 projects to achieve logistical and economic efficiency.

Decentralized Production Potential

One potential advantage of bio-based hydrogen production is its ability to support decentralized hydrogen generation. Aligning production with bio-resource availability—such as agricultural residues, forestry waste, and organic municipal waste—can help reduce transportation and storage costs. This approach could make bio-hydrogen viable in rural and semi-urban areas with abundant biomass resources. Efforts must be channelled to implement demonstration-level projects before implementing wider policy guidelines. Future policies can be enhanced by leveraging the lessons learned from MNRE's biogas program, establishing rural biogas plants for clean cooking, lighting, and meeting thermal and small power demands.

While biogas or producer gas can be used directly as decentralized green fuels, converting them to hydrogen despite the additional cost offers greater environmental and strategic advantages. Hydrogen enables zero-emission use at the point of consumption. It is more versatile across sectors such as mobility, refining, and industry, where direct use of methane or producer gas is not feasible. This conversion supports long-term decarbonization goals and provides a cleaner, future-ready energy carrier.

To assess the maturity and diversity of bio-based hydrogen technologies, examining key projects underway in India and globally is helpful. The Table 2 highlights representative initiatives using varied feedstocks and conversion technologies, reflecting the evolving landscape of bio-hydrogen production.

Table 2 Selected Bio-Based Hydrogen Projects – India and Global

Project Name & Location	Feedstock Type	Technology Used	Hydrogen Output (kg/day)	Project Status	Key Notes
Gensol–Matrix Bio-H_2 Project (India)	Organic municipal bio-waste	Plasma-Induced Radiant Energy-Based Gasification (GH_2-PREGS)	1,000	Under development	India's first large-scale bio-hydrogen project; ₹164 crore EPC contract.
ISA–NDDB Ramnagar Dairy Project (India)	Biogas from dairy waste	Anaerobic digestion + electrolysis hybrid	Not disclosed	Announced	Aims to integrate solar and biogas for green hydrogen production.
Sea6 Energy (India)	Red seaweed (macroalgae)	Enzymatic hydrolysis + fermentation + gasification (R&D stage)	Lab-scale	Pilot R&D	Exploring seaweed as a sustainable biomass source for hydrogen production.
Biezel Green Energy (BGE) – Bangalore, Karnataka, India	Organic waste (agri-residue, poultry litter, etc.)	Thermally Accelerated Anaerobic Digestion (TAD)	Not disclosed	Commissioned	Utilizes proprietary TAD reactors to produce hydrogen-rich bio-hythane and bio-coal.
Watomo Energies & Biezel Green Energy JV – Khandwa, Madhya Pradesh, India	Biomass (30 tonnes/day)	Thermally Accelerated Anaerobic Digestion (TAD)	1,000	Announced	India's first commercial-scale biomass-based hydrogen plant; ₹24 crore investment.
Indian Institute of Science (IISc) – Bangalore, Karnataka, India	Agricultural residue	Oxy-steam gasification + syngas purification	~100 g/kg biomass	Pilot R&D	Developed a two-step process yielding 100 g of hydrogen per kg of biomass; collaboration with IndianOil for scaling up.
NTPC NETRA – Simhadri, Andhra Pradesh, India	Municipal solid waste and agri-waste (25 tonnes/day)	Plasma Oxy Gasification + gas membrane separation + PSA	1,000	Under development	World's first plasma oxy gasification plant for high-purity green hydrogen production; also generates electricity from CO.

Project Name & Location	Feedstock Type	Technology Used	Hydrogen Output (kg/day)	Project Status	Key Notes
Enerkem Varennes Carbon Recycling Plant (Canada)	Biomass and non-recyclable waste	Gasification + catalytic conversion	~340,000 (projected)	Under construction	Scheduled for 2025; will produce biofuels and hydrogen from 200,000 tonnes/year of waste.
Concord Blue Reformer Projects (Germany, India, USA, Japan)	Various biomass and waste materials	Steam thermolysis-based gasification	Varies by project	Operational	Deploys patented technology for CO_2-free hydrogen and bioenergy production.
MACBETH Project (EU)	Biogas	Autothermal reforming in fluidized bed membrane reactor	Pilot-scale	R&D phase	Focused on producing high-purity hydrogen for various applications.

These examples demonstrate the range of bio-hydrogen technologies under development, from thermochemical to biochemical pathways. India's growing participation, as seen in projects like Gensol–Matrix and ISA–NDDB, suggests an emerging potential for domestic scalability.

An updated and comprehensive list of global and national hydrogen projects, including biomass-based ones, is maintained by the International Energy Agency (IEA) and the Ministry of New and Renewable Energy (MNRE), Government of India. The QR codes of their respective web portals are presented below.

IEA's Hydrogen Production Projects Interactive Map (Project-level data on low-emissions hydrogen production worldwide)

Green Hydrogen Projects in India (Maintained by Ministry of New and Renewable Energy, Government of India)

Scaling up green hydrogen production in India requires a multi-pronged approach. All production technologies should be granted a level playing field and ample opportunity to demonstrate their production capability, economic viability, and scalability without preferential treatment for any single technology. As per data from the Ministry of New and Renewable Energy (MNRE), as of June 2025, India has at least two operational electrolyzer manufacturing facilities, two facilities under construction, and seventeen additional projects that have been announced and are in various planning and development stages. Strengthening domestic electrolyzer manufacturing, setting efficiency benchmarks, and addressing bio-based production challenges will be essential. While bio-hydrogen remains in the research phase, its role in decentralized production should be explored alongside the mainstream adoption of electrolyzer-based hydrogen generation.

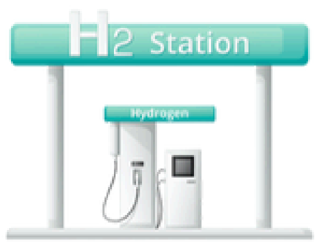
2.2 Storage and Transport

Efficient storage and transportation are critical to scaling up green hydrogen adoption. Unlike conventional fuels, hydrogen has a low volumetric energy density, making storage and transport technologically challenging and cost-intensive. Developing dedicated infrastructure, optimizing existing assets, and leveraging innovative approaches such as digital twins (discussed in detail in subsequent text) can significantly accelerate the commercial viability of hydrogen storage and transport.

Pipeline Infrastructure and Hydrogen Storage in Pipelines
Most existing hydrogen is transported through high-pressure cylinders, cryogenic liquid tanks, or blended with natural gas in existing pipelines. High-pressure hydrogen cylinders typically operate at 200 to 700 bar pressures, while blending with natural gas generally occurs at concentrations up to 20% by volume, depending on local regulations and infrastructure compatibility. However, the lack of dedicated hydrogen pipelines increases transportation costs and restricts large-scale deployment. Expanding a dedicated hydrogen pipeline network would require substantial investment, regulatory alignment, and technical modifications, as hydrogen's small molecular size makes it prone to leakage and embrittlement in traditional steel pipelines.

The absence of a widespread hydrogen pipeline network leads to higher transportation costs and limits market penetration. Retrofitting existing natural gas pipeline is an option, but material compatibility and safety concerns must be addressed. With appropriate material upgrades and pressure management, pipelines can also serve as a viable option for temporary or buffer hydrogen storage, offering an alternative to dedicated storage facilities. This method injects hydrogen into existing pipeline networks, reducing the immediate need for separate storage infrastructure. Repurposing natural gas pipelines for Hydrogen transportation via pipelines remains limited due to the absence of dedicated infrastructure. Hydrogen transport and storage could provide a cost-effective and scalable solution. However, this would require material modifications to prevent hydrogen-induced embrittlement and permeability losses. Research and demonstration on blending hydrogen with natural gas and using reinforced pipeline materials is ongoing to address these challenges.

Digital Twins for Hydrogen Storage Optimization
Digital twin technology—virtual models that simulate real-world systems—offers significant potential in optimizing hydrogen storage solutions. In the context of hydrogen, digital twins are increasingly being employed to model the thermomechanical behavior of storage vessels under different operating conditions, such as pressure cycling, temperature fluctuations, and hydrogen permeation. These digital models allow for accelerated testing of materials, pressure limits, and performance under varying conditions, reducing the time and cost associated with physical trials. For instance, digital twins can simulate the effects of hydrogen embrittlement on metal liners or composite overwraps, enabling predictive maintenance and safer design margins.



Leading institutions like Germany's Fraunhofer Institute and private sector players like Siemens and ANSYS are developing digital twin frameworks tailored to hydrogen infrastructure, including Type IV composite cylinders and underground storage systems. These platforms integrate sensor data with multiphysics simulations to monitor degradation in real-time and forecast lifespan under high-pressure usage (e.g., 350–700 bar).

Researchers are exploring using digital twins to improve the design and efficiency of hydrogen storage cylinders. Current research in India is focused on scaling hydrogen storage cylinders from Technology Readiness Level (TRL) 3 to TRL 7, moving from early-stage proof-of-concept studies to near-commercial deployment. Digital twins in this process enable continuous performance monitoring, predictive maintenance, and real-time optimization, making storage solutions more efficient and cost-effective.

Infrastructure Constraints in Hydrogen Storage and Transport

Hydrogen storage and transport infrastructure face multiple constraints, including:

- **Cryogenic Storage Challenges**
  Hydrogen must be cooled to -253°C for liquefaction, requiring specialized cryogenic tanks. This process is energy-intensive, adding to overall costs.

- **High-Pressure Cylinder Transport**
  In India, compressed hydrogen is commonly transported in cylinders at pressures around 300-350 bar due to manufacturing and safety considerations. Globally, hydrogen cylinders operating at up to 700 bar pressures are used.

- **Lack of Hydrogen Hubs**
  Unlike LNG terminals, dedicated hydrogen storage hubs and refueling stations are scarce, making large-scale distribution difficult. In addition to the above, safe, scalable, and sustainable hydrogen infrastructure requires a comprehensive understanding of hydrogen's molecular behavior under varying atmospheric conditions.

Overcoming these infrastructure bottlenecks will require coordinated efforts between policymakers, industry players, and research institutions. Standardizing pipeline materials, investing in digital twin simulations, and developing cost-effective cryogenic and high-pressure storage solutions will enable a reliable and efficient hydrogen supply chain.

In parallel, advancing liquid hydrogen carriers—such as liquid organic hydrogen carriers (LOHCs) and ammonia—can offer alternative pathways for long-distance transport and large-scale storage, particularly where pipelines or compression are less feasible.

2.3 Utilization

The adoption of green hydrogen (GH_2) in India should be guided by domestic priorities rather than global trends. Policymaking in the hydrogen sector has predominantly focused on the supply side, with limited focus on demand dynamics. However, the long-term success of hydrogen projects depends on ensuring sustained demand across different sectors. A demand-driven strategy is essential to align hydrogen utilization with national economic and environmental objectives.

Fine Chemicals

Hydrogen is a critical feedstock in the fine chemicals industry, where it is used in various chemical synthesis processes to produce high-value compounds such as Menthol, Citronellol, Hydroxycitronellal, Geraniol, Nerol, Cinnamyl Alcohol, Phenyl Ethyl Alcohol, as well as hydrogenated oils and fats derived from linoleic, oleic, and stearic acids, including palm oil. Transitioning to green hydrogen in this sector requires stable supply chains and cost-competitive production. While green hydrogen can replace grey hydrogen in fine chemical manufacturing, challenges such as high production costs and limited domestic electrolyzer capacity must be addressed. Indian specialty chemical owners are -

paying anywhere from 35 to 45 INR per Nm3 for hydrogen, which translates to approximately ₹420–540 per kg (based on the conversion: 1 kg H_2 ≈ 11.1 Nm^3 at standard conditions). Lowering the cost of developing cost-effective hydrogen production pathways tailored for fine chemical applications will be necessary to drive industry adoption.

Cooking

India can explore hydrogen as a clean fuel for cooking, reducing dependence on liquefied petroleum gas (LPG) and biomass. While most global hydrogen utilization strategies focus on industrial and mobility applications, integrating hydrogen into domestic energy could enhance energy security.

One of the key research areas should be indigenous safe burner development, ensuring efficient and safe hydrogen combustion for household use. However, health and safety regulations must be established before large-scale implementation, as hydrogen's combustion characteristics differ from traditional fuels.

Highlighting the health benefits of hydrogen as a clean cooking fuel could unlock significant growth in a new market sector. This initiative aligns with Sustainable Development Goals (SDGs) by promoting clean energy access, improving indoor air quality, and reducing reliance on fossil fuel-based cooking solutions.

Hard-to-abate sector : Cement, Steel and Bulk Chemical Industries

Decarbonizing hard-to-abate industries such as cement, steel, and chemicals is a significant challenge due to their dependence on high-temperature processes and fossil fuel-based feedstock. Green hydrogen can be a potential alternative to decarbonize these sectors, but high costs and technological barriers hinder its adoption.

- **Cement Industry :** GH_2 has not yet been widely tested for cement manufacturing. As of 2024, only a limited number of global pilot initiatives are underway. Notably, CEMEX (Mexico) and Heidelberg Materials (Europe) have announced small-scale trials to assess hydrogen's role as a partial fuel replacement. However, there are no major publicly known trials in India yet.

- **Steel Industry :** The hydrogen-based direct reduction of iron (H-DRI) presents a promising pathway to significantly reduce carbon emissions in steel production by replacing carbon-intensive blast furnaces with hydrogen as the reducing agent. The capital expenditure for establishing H-DRI plants is currently higher than conventional steelmaking routes, primarily due to the cost of electrolyzers for green hydrogen production and the need for retrofitting or building new steel plants optimized for hydrogen use.

  Globally, pilot and commercial-scale projects are underway to demonstrate the viability of H-DRI. For example, companies like SSAB (Sweden), ArcelorMittal (Europe), and POSCO (South Korea) have launched projects to integrate green hydrogen in steel production, aiming for significant emission reductions by 2030. India's steel sector, being one of the largest globally, has initiated research collaborations and feasibility studies but has yet to see large-scale H-DRI deployment.

- **Bulk Chemical Industry :** GH_2 can replace grey hydrogen in ammonia and methanol production, but cost-related challenges persist.

- **Fertilizer Industry :** The Solar Energy Corporation of India (SECI) is navigating pricing uncertainties and regulatory challenges to finalize green hydrogen tenders for the fertilizer industry. Clear policy frameworks and demand-side incentives are required to ensure the successful transition of the fertilizer sector to GH_2-based production.

Mobility

The transportation sector is a key area for hydrogen utilization, but Fuel Cell Electric Vehicles (FCEVs) face significant adoption barriers:

- **High Costs:** The fuel cell stack, the heart of an FCEV, is a complex and expensive component. It relies on precious metals, particularly platinum, as catalysts. Platinum's scarcity and high price significantly increase production costs.
- **Material Compatibility Issues:** The small molecular size of hydrogen makes it prone to leakage, requiring specialized storage materials that increase costs.
- **Infrastructure Limitations:** The limited availability of hydrogen refueling stations significantly restricts the widespread adoption of fuel cell electric vehicles (FCEVs), as consumers and fleet operators face challenges in accessing convenient and reliable refueling Infrastructure.

India lacks streamlined and comprehensive certification mechanisms for hydrogen-powered mobility, affecting investor confidence and large-scale adoption. Additionally, defining the useful life of hydrogen vehicles is essential for financial institutions to offer viable loan and insurance products tailored to FCEVs.

For hydrogen adoption to be successful, supply-side policies must be complemented by demand-side strategies. Fine chemicals, cooking applications, hard-to-abate industries, and mobility each present unique challenges and opportunities. Strengthening demand forecasting, regulatory frameworks, and financing mechanisms will be critical for ensuring sustainable hydrogen utilization across sectors.

2.4 Addressing Supply-Demand Gaps

India's green hydrogen strategy must address a fundamental question: should the focus be on converting the existing grey hydrogen industry to green or creating new demand centers for green hydrogen. Currently, the country lacks demand-side incentives, limiting large-scale hydrogen adoption's commercial viability. Green hydrogen projects risk stagnation after the initial demonstration phase without clear policy mandates and long-term market signals.

Bridging the Demand-Side Gap

Unlike renewable power, which has benefited from Renewable Purchase Obligations (RPOs), India's green hydrogen sector lacks similar mandates to ensure sustained demand. Introducing sector-specific green hydrogen utilization mandates similar to RPOs in the solar sector could accelerate adoption in industries such as fertilizers, refining, steel, and chemicals. Without such mechanisms, there is little certainty that green hydrogen supply will find adequate demand post-demonstration projects.

Furthermore, after the current demonstration projects conclude in the next three to five years, the stakeholders must ensure that supporting infrastructure is ready for commercial scale-up. This includes developing hydrogen storage, transportation networks, and refueling stations. A clear roadmap is needed to transition from pilot-scale initiatives to an operational green hydrogen market.

Hydrogen Valleys: Implementation Timelines and Challenges

The realization of integrated green hydrogen ecosystems through India's Hydrogen Valley initiatives presents a complex landscape of challenges and considerations. Funding dynamics, in particular, are observed to exert influence over the implementation timeline. The entire value chain of these valleys must be evaluated to determine their feasibility and economic viability. Adequate financial support, streamlined regulatory approvals, and private sector participation are critical for ensuring Hydrogen Valleys become functional hubs for green hydrogen deployment.

Grid Readiness for Renewable Hydrogen Production

A thriving green hydrogen economy depends on the ability of the electricity grid to absorb variable renewable energy (VRE) sources. The resilience of India's grid to handle intermittent solar and wind generation for green hydrogen production needs to be assessed. Without proper grid balancing mechanisms, the large-scale deployment of electrolyzers could strain the grid, leading to inefficiencies and energy curtailment. Strengthening grid infrastructure and integrating advanced energy storage solutions will be essential for optimizing green hydrogen production from renewables.

Assessing Real Market Demand for Electrolyzers

The anticipated surge in electrolyzer demand raises concerns about whether genuine industrial needs or speculative market projections drive it.

It is essential to critically evaluate the demand for electrolyzers by conducting detailed market assessments, engaging directly with industry stakeholders, and analyzing real project pipelines from end-users rather than relying on assumed industry expansion. Overestimating demand could lead to supply chain mismatches, while underestimating it could slow down domestic manufacturing initiatives.

India must ensure a demand-backed approach to electrolyzer production to avoid inefficiencies in scaling up manufacturing capacity. To bridge the supply-demand gap, India needs to introduce demand-side mandates, ensure infrastructure readiness for post-demonstration projects, and expedite the implementation of Hydrogen Valleys. Additionally, assessing grid capacity for renewable hydrogen production and validating actual electrolyzer demand will be crucial.

A balanced approach that aligns supply expansion with actual market demand will be key to ensuring the long-term viability of India's green hydrogen economy.

03 Key Focus Areas

In assessing India's current green hydrogen development trajectory against its 2030 targets, five critical parameters have been identified as central to bridging the gap between ambition and on-ground progress. These focus areas emerged from extensive deliberations during the workshop and analysis of the broader sectoral challenges.

The following subsections examine each of the five focus areas in greater detail, outlining the specific challenges and potential strategies for resolution.

3.1 Landscape

The global financing landscape for green hydrogen is evolving rapidly, with a noticeable shift from international collaboration to more inward-looking trade policies. Countries prioritize domestic production capabilities, incentivize local supply chains, and implement protective trade measures to secure energy independence. This shift has significant implications for green hydrogen investments as nations look to balance economic competitiveness with sustainability goals. Successful case studies, such as the NEOM project in Saudi Arabia, highlight how large-scale financing structures can be established. In this case, many banks collaborated to provide funding, demonstrating the importance of multi-stakeholder investment approaches in scaling hydrogen projects. Such examples underscore the need for financial innovation and risk-sharing mechanisms to make green hydrogen commercially viable.

Unlike traditional infrastructure projects, green hydrogen should be viewed as a commodity business rather than purely an infrastructure-driven project. Hydrogen is a molecule that requires efficient production, distribution, and trading mechanisms akin to other energy commodities like natural gas. Consequently, financial strategies should focus on market creation, cost competitiveness, and integration into existing industrial value chains rather than solely emphasizing capital-intensive infrastructure deployment. Aligning investment frameworks with this perspective will ensure the green hydrogen economy's long-term scalability and financial sustainability.

The role of corporate social responsibility (CSR) in financing has also evolved, transitioning from a philanthropic approach to a more developmental model. The Table 3 summarizes some notable CSR-backed initiatives focused on green hydrogen in India.

Organization / CSR Entity	Initiative Description	Location	Key Outcomes
Horiba India	Funded three research projects at IIT Delhi focusing on green hydrogen production via H-SOEC, low-cost EV motors, and smart fabrics.	IIT Delhi	Advancement in green hydrogen technology and support for scientific education.
ReNew Energy Global	Established the ReNew Centre of Excellence at IIT Delhi to foster research in renewable energy and green hydrogen.	IIT Delhi	Promotion of R&D in green hydrogen and capacity building.

Organization / CSR Entity	Initiative Description	Location	Key Outcomes
JSW Group	The JSW Technology Hub at IIT Bombay supports research on decarbonization and green hydrogen technologies.	IIT Bombay	Development of innovative solutions for green hydrogen production.
Reliance Foundation	Supports various sustainability initiatives, including those aligned with green hydrogen development, as part of its broader CSR activities.	Pan-India	Contribution to sustainable energy projects and community development.
REC Limited	Installed a 2 MW rooftop solar plant at IIT Madras, facilitating research and education in renewable energy indirectly supporting green hydrogen initiatives.	IIT Madras	Provision of clean energy for academic research and infrastructure.

Instead of short-term charitable contributions, corporations are increasingly directing CSR funds toward sustainable development initiatives, such as supporting startups, incubating hydrogen-related technologies, and collaborating with academic institutions. This shift enhances long-term impact by fostering innovation and strengthening the green hydrogen ecosystem. Encouraging corporates to participate in early-stage research and commercialization efforts can help de-risk investments and accelerate the market readiness of emerging hydrogen technologies.

Challenges in Green Financing in India

Indian banks are demonstrating a willingness to support green hydrogen financing, but they lack the balance sheet depth and technological expertise required to assess project risks effectively. Unlike conventional renewable energy sectors such as solar and wind, which have well-established financial models, green hydrogen remains a relatively new domain with uncertain revenue streams. Financial institutions struggle to evaluate their long-term viability, making risk assessment a significant challenge. The Reserve Bank of India (RBI) has set expectations for banks to conduct multi-scenario analyses and ensure full disclosure of funds raised for green investments, thereby increasing transparency and building confidence among global investors. However, integrating financial strategies with evolving green hydrogen technologies remains a complex task that requires structured frameworks and regulatory clarity.

One of the primary concerns for financial institutions is the high-risk perception associated with green hydrogen projects. Renewable energy projects such as solar and wind have a track record, making them reliable investment options. In contrast, green hydrogen projects require additional assurances regarding future returns and associated risks. The absence of proven financial performance makes lenders hesitant to commit capital at scale. Furthermore, the G20 Sustainable Finance Working Group has highlighted bankability concerns, emphasizing skepticism about green hydrogen's revenue-generating potential. In this context, the credibility of investors becomes a critical factor, and government intervention is essential to enhance project viability. Strategic policy support, such as sovereign guarantees or viability gap funding, could play a key role in mitigating financial risks and attracting private investments.

The existing financing models in India, which predominantly rely on traditional loans, may not be suitable for green hydrogen projects that require substantial upfront capital and have extended payback periods. Unlike conventional energy infrastructure, green hydrogen involves significant research, development, and scale-up costs, necessitating alternative financial mechanisms such as blended finance, concessional loans, and grants. Notably, grants for climate adaptation components remain limited, further constraining the financial feasibility of early-stage projects. Additionally, the lack of collateral poses another barrier. The absence of historical data on green hydrogen projects makes them inherently risky. Government-backed collateral mechanisms could enhance credibility and de-risk investments, encouraging financial institutions to participate more actively.

State financial health also plays a crucial role in green hydrogen investment viability. Weak financial positions of state utilities and delays in power purchase agreement (PPA) payments increase risk perception among investors, potentially hindering large-scale project deployment. Financial stability at the state level through fiscal reforms and payment security mechanisms will be critical for fostering investor confidence. Additionally, defining a standardized green hydrogen taxonomy is essential to streamline investments, create regulatory certainty, and align India's financial sector with international green finance standards. A well-defined taxonomy would help differentiate green hydrogen from other hydrogen production methods, facilitating targeted financial support and reducing ambiguity in project classification. Addressing these challenges through policy interventions, financial innovation, and risk-mitigation strategies will be crucial for unlocking large-scale green hydrogen financing in India.

Investor's Perspectives

Investors are increasingly willing to finance green hydrogen projects through loans rather than grants, reflecting a preference for structured financial returns over outright funding support. While the Reserve Bank of India (RBI) is working on creating a repository of bankable projects, including green hydrogen ventures, the lack of well-defined financing mechanisms continues to pose challenges. A key consideration in risk assessment is whether climate-related risks are treated as an independent factor or as a subsumed component within broader financial risk models. The current approach essentially integrates climate risks within general financial assessments. Still, there is a growing recognition of the need for scenario-based risk analysis to understand long-term project viability and resilience better.

The capital-intensive nature of green hydrogen projects necessitates guaranteed returns, especially when large-scale investments are involved. However, indiscriminate subsidies for major industrial players could hinder cost innovation, as companies with strong financial backing may lack the incentive to drive efficiency improvements. Instead, targeted public-sector support should focus on smaller firms and startups, fostering a competitive ecosystem that encourages technological advancements and cost reductions over time. India is strategically positioned to capitalize on green hydrogen development due to its abundant renewable energy resources and the potential for grid enhancements that can accommodate increased variable renewable energy (VRE) integration. However, past experiences with Battery Energy Storage Systems (BESS) highlight the risks of delayed adoption, underscoring the need for a proactive, collaborative approach to seize the opportunity before other markets establish dominance.

Investors seek sovereign guarantees for large-scale financing. Projects such as Saudi Arabia's NEOM secured international financing, including the government's Public Investment Fund (PIF) support. Indian banks require similar government assurances to mitigate perceived risks and unlock substantial capital inflows. Dedicated green hydrogen bonds could effectively attract institutional investors, offering structured financial instruments aligned with sustainability goals. Additionally, combining public and private sector funding, blended finance models could help de-risk projects and facilitate investment at scale. To ensure a stable demand for green hydrogen, policymakers should introduce Green Hydrogen Purchase Obligations (GHPOs), mandating specific industries to procure a fixed share of their hydrogen requirements from green sources. This approach would create a guaranteed off-take, reducing revenue uncertainties and strengthening investor confidence in the sector. Establishing these financial and policy mechanisms will be crucial in securing long-term investment and fostering India's robust green hydrogen market.

3.2 Challenges of Funding Timelines

Delayed disbursement of committed funds is emerging as a significant barrier to the timely execution of green hydrogen initiatives in India. Programs such as the Hydrogen Valley projects, which were designed to demonstrate integrated hydrogen ecosystems at scale, have faced notable funding lags. Despite early announcements and initial enthusiasm, fund releases have been delayed by over 12 months in several cases, impeding early momentum and affecting stakeholder confidence. This disrupts project planning cycles and adversely affects private sector participation, as companies perceive heightened financial and operational risks in the absence of predictable public support.

Timely funding is critical in emerging sectors like green hydrogen, where technology costs remain high, commercial models are still evolving, and first-mover risks are substantial. Unlike mature sectors, where private financing can often bridge temporary gaps, green hydrogen projects depend heavily on catalytic public-sector funding during the early stages to de-risk investments, validate business models, and achieve technology demonstration. Inconsistent funding flows undermine these objectives, causing pilot projects to stall, delaying technology validation timelines, and diminishing India's ability to demonstrate global leadership in hydrogen innovation.

The current funding delay patterns are partly due to procedural complexities in administrative approvals, the absence of streamlined fund release mechanisms linked to project milestones, and cautious approaches toward disbursement amid evolving regulatory frameworks. Without reforms to expedite the flow of funds, India risks losing critical years needed to build a first-mover advantage, especially as other countries aggressively push forward with well-funded national hydrogen programs.

In the future, it is essential to introduce milestone-based disbursement frameworks with clear performance-linked payment structures for green hydrogen projects. Early-stage projects, particularly in strategic initiatives like Hydrogen Valleys and electrolyzer manufacturing, must provide timely financial support to maintain sectoral momentum. Transparent timelines, accountability mechanisms, and simplified fund release protocols will restore trust among industry stakeholders and ensure that flagship initiatives translate into on-ground achievements.

3.3 Testing and Standards

Standardization, certification, and testing are foundational pillars for establishing a competitive green hydrogen (GH_2) ecosystem in India. Developing robust industrial standards that align with global benchmarks will ensure safety, efficiency, and interoperability while enabling Indian companies and startups to participate in international markets. Without common technical and safety standards, GH_2 producers may face trade barriers and limited market access, restricting their ability to compete on a global scale.

There is an information asymmetry regarding hydrogen-related regulations, technologies, and market trends. This asymmetry hampers the ability of businesses, especially startups, to navigate the evolving hydrogen economy and scale their innovations globally. Establishing open-access knowledge platforms, industry forums, and government-backed research initiatives can improve transparency and support informed decision-making, accelerating the sector's growth.

Certification mechanisms play a crucial role in verifying the environmental credentials of GH_2, ensuring it meets sustainability and carbon-intensity criteria. India needs to implement certification frameworks that are internationally recognized while maintaining a balance between regulation and industry growth. Excessive regulatory interventions could slow market adoption, whereas a streamlined, industry-friendly certification process would enhance investor confidence and facilitate GH_2 trade.

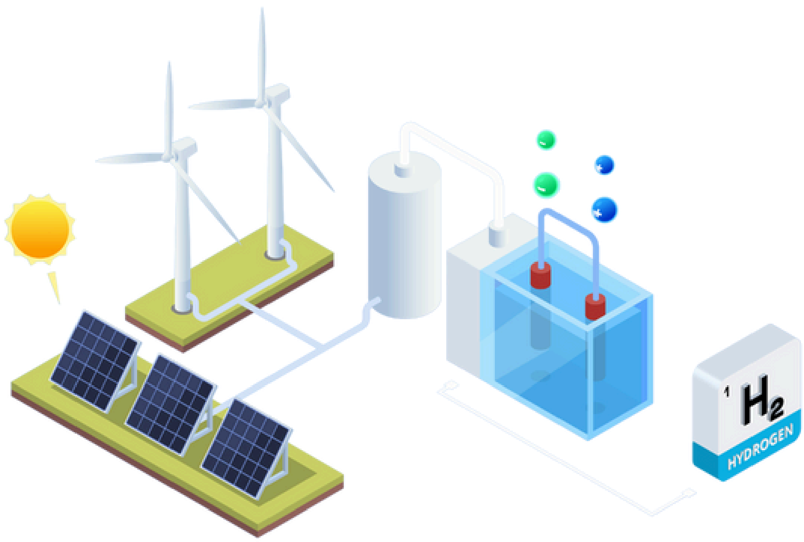
Hydrogen-related testing, covering safety assessments, material compatibility studies, and performance evaluations, requires significant capital investment. Independent testing facilities are expensive to set up and maintain, making centralized national testing centers and collaborative initiatives between -

academia, industry, and regulatory bodies essential. These facilities should focus on fuel cell validation, pipeline material assessment, and hydrogen storage safety, ensuring that infrastructure and technology meet domestic and international safety requirements.

3.4 Research and Development

The advancement of green hydrogen (GH2) technologies is crucial for a sustainable energy future. Key aspects of research and development are pivotal to realizing this potential. This sub-section explores the critical need for fundamental research on hydrogen safety, a cornerstone for widespread adoption. Furthermore, it analyzes the challenges and opportunities inherent in fostering effective industry-academic collaboration, recognizing these partnerships' vital role in driving innovation. Finally, it outlines promising research areas in GH2, highlighting the technological frontiers that demand focused attention to accelerate progress in this transformative field.

Need for Fundamental Research on Hydrogen Safety



Hydrogen safety is a critical aspect of the green hydrogen ecosystem, requiring thorough research, standardized protocols, and risk mitigation strategies to ensure safe production, storage, transportation, and utilization. Given hydrogen's unique properties—such as its low ignition energy, high diffusivity, and potential for embrittlement in metals—developing safety frameworks is essential to prevent accidents and build public confidence. A comprehensive and systemic approach to safety is paramount-throughout the entire lifecycle of hydrogen projects. A single incident can significantly impede progress and undermine the cumulative efforts invested, making proactive risk management a top priority.

A deeper understanding of hydrogen safety is needed, focusing on quantifying fundamental parameters such as explosion limits, dispersion behavior, and material compatibility. Establishing benchmarks for hydrogen safety across different applications will be crucial in guiding industry best practices. Comprehensive safety protocols must be integrated at every stage, from electrolyzer operation and pipeline transport to refueling infrastructure and industrial applications.

Effective risk communication ensures regulators, policymakers, and emergency response teams are well-prepared to handle hydrogen-related incidents. Clear guidelines on hazard identification, mitigation strategies, and emergency response procedures must be established and disseminated widely. Standardized training programs and simulation-based drills can equip response teams with the necessary skills to manage potential hydrogen-related risks.

Investing in dedicated research and testing facilities focused on hydrogen safety will be necessary to support ongoing advancements in the sector. Collaborative efforts between research institutions, industry stakeholders, and regulatory bodies can accelerate the development of comprehensive safety standards tailored to India's infrastructure and environmental conditions. By prioritizing safety at every stage, India can ensure that hydrogen adoption progresses responsibly and sustainably, minimizing risks and fostering stakeholder confidence.

Challenges in Industry-Academic Collaboration

India's hydrogen ecosystem is supported by key initiatives such as the National Green Hydrogen Mission (NGHM), the International Centre for Hydrogen Energy Technologies (ICHET), hydrogen research centers at premier institutions like IIT Madras and IIT Bombay, and emerging regional hydrogen hubs in states including Gujarat, Maharashtra, and Tamil Nadu.

Industry-academic collaboration in research and innovation for green hydrogen faces several structural and operational challenges. Academia is often expected to lead the way in developing new technologies, with industry and policymakers waiting for academic insights before taking action. However, this dynamic can be inefficient if academic research is not aligned with industry needs. While academia focuses on deep exploration and fundamental understanding, industry prioritizes practical solutions with clear timelines and targets. This divergence in priorities can slow innovation and delay the commercialization of research findings. For collaboration to be effective, academia must adopt a more outcome-oriented approach that balances depth with applicability.

One of the key obstacles is the fear of failure. Failure in research is often stigmatized. However, it should be seen as an essential part of the innovation process. Research efforts tend to focus on already proven problems rather than exploring uncharted areas where failure might be possible. This risk-averse culture limits disruptive innovation. Both industry and government must foster an environment where failure is understood as a stepping stone to progress, allowing researchers to take calculated risks in developing breakthrough technologies.

There is also a systemic mismatch between academia and industry regarding incentives and priorities. While academic institutions emphasize publications and PhD completions, the industry is driven by cost efficiency and immediate solutions. This difference in focus can result in research not directly applicable to industrial needs. Intellectual property (IP) sharing is another critical challenge. A lack of trust between academia and industry often hinders knowledge transfer, as companies fear losing their competitive advantage, and universities worry about not receiving due credit for their contributions. Establishing clear frameworks for IP ownership and benefit-sharing is necessary to encourage collaboration.

The skill development gap further complicates industry-academic partnerships. The green hydrogen industry requires a workforce trained in specialized areas such as electrolysis, hydrogen storage, and fuel cell technology. However, academic curricula are often not updated to reflect these emerging needs. Targeted skill development programs must be designed to bridge this gap and prepare students for industry roles.

Time scale differences create additional friction, as industries often require immediate solutions, whereas academic research operates on longer timelines. This disconnect can lead to frustration and missed opportunities. Similarly, high overhead costs in academic research can make the industry hesitant to engage in collaborative projects. A more flexible funding mechanism that reduces administrative burdens and incentivizes long-term partnerships is needed.

A crucial question is whether principal investigators (PIs) can move beyond conventional academic roles to engage meaningfully with industry. Many industries require urgent solutions, yet long-term investments in research must not be overlooked. The challenge lies in balancing immediate industrial demands with sustained innovation. Furthermore, current research grant mechanisms do not facilitate joint project proposals from academia and industry. Each party submits proposals suited to their interests rather than co-developing them from the outset. A revised funding structure that encourages collaborative proposal writing and joint execution could significantly enhance the effectiveness of industry-academic partnerships.

For green hydrogen research to thrive, systemic changes are required to bridge the gap between academia, industry, and government.

Addressing issues of trust, timelines, incentives, and failure perception will be key to fostering a research ecosystem that drives real-world impact.

Opportunities in Industry-Academic Collaboration

Industry-academic collaboration in green hydrogen research presents numerous opportunities to accelerate innovation and commercialization. One such initiative is the establishment of electrolyzer testing facilities, which will aid in standardizing performance metrics and validating electrolyzer efficiency under real-world conditions. These facilities will ensure reliability and scalability while fostering industry confidence in emerging technologies. Beyond testing, bridging the gap between laboratory-scale research (Technology Readiness Level 3) and commercial deployment (TRL 7 and beyond) remains a crucial challenge. Strengthening this transition requires dedicated funding, pilot-scale demonstrations, and structured pathways to move academic innovations toward industrial adoption.

A shift toward a problem-centric approach is essential for maximizing research impact. Instead of developing solutions in isolation, research should begin with identifying critical industry challenges and designing targeted solutions. This ensures that outputs are practical, market-ready, and aligned with industry needs. Academic research must balance science-based, technology-driven, and industry-oriented studies, with interdisciplinary research being key due to the complex and cross-sectoral nature of the green hydrogen ecosystem.

Academicians must also demonstrate in real-world settings that green hydrogen projects have revenue-generating potential, which would increase industry engagement and attract investment. A critical step in this direction is defining a clear green hydrogen taxonomy to ensure standardization and facilitate investor decision-making. However, industries also need to articulate their needs clearly. A structured tri-party arrangement bringing together industry, academia, and policymakers could enable transparent discussions on research priorities and commercialization strategies, ensuring alignment of expectations.

Institutional performance parameters must evolve to prioritize real-world impact, industry collaboration, and technology transfer in green hydrogen development. Academic projects should address pressing industry challenges, while industries must accommodate academic constraints to enable effective partnerships. Breaking down silos through interdisciplinary departments will foster knowledge exchange and a holistic research environment. Decoupling academic and industrial timelines and establishing a dedicated translational research institute for high-TRL projects can bridge the gap between fundamental research and commercialization.

By addressing these opportunities systematically, industry-academic collaboration in green hydrogen can be transformed into a powerful engine for technological advancements, economic growth, and energy transition. The key lies in fostering an ecosystem that values interdisciplinary cooperation, problem-driven research, and structured pathways to scale innovations.

Areas of Research in Green Hydrogen

Research in green hydrogen must be rooted in a deep understanding of the fundamental behavior of the hydrogen molecule to drive technological advancements effectively. Hydrogen's small molecular size, high diffusivity, and reactivity present unique challenges and opportunities across various applications. These span all aspects and technologies for generation, transportation, storage, and utilization. Electrolysis technology, the cornerstone of green hydrogen production, also requires continuous innovation based on molecular-level insights. Improving catalyst efficiency and stability by designing catalysts based on non-noble metals, optimizing membrane conductivity, finding alternative membranes/diaphragms with similar/better performances (conductivity and stability) compared to Zirfon (proprietary) for alkaline operating conditions, and minimizing catalyst and membrane degradation mechanisms will enhance electrolyzers' overall energy conversion efficiency and lifetime. Developing electrocatalysts and membranes for seawater electrolysis is another area of active research that presents several challenges related to catalysts, their life, and efficiency.

Moreover, breakthroughs in hydrogen purification, compression, and liquefaction are essential to overcoming storage and transport bottlenecks. Research into solid-state hydrogen carriers, metal hydrides, and other novel storage solutions could offer safer and more efficient alternatives to conventional high-pressure or cryogenic methods. Investigating hydrogen's interaction with different materials, especially in storage and transportation systems, is crucial for developing efficient and safe infrastructure.

Research on hydrogen embrittlement, permeability, and adsorption characteristics can advance the design of advanced alloys and composite materials that enhance durability and minimize losses in pipelines, storage tanks, and fuel cells. Similarly, understanding hydrogen's combustion dynamics in various environments can facilitate its application in industrial heating, power generation, and mobility. Computational modeling and quantum simulations can aid in predicting hydrogen behavior under extreme conditions, accelerating the development of next-generation hydrogen technologies.

Hydrogen combustion, although providing a clean substitute for fossil fuels due to its absence of carbon emissions, has numerous technical and safety concerns. A principal concern is its elevated flame speed and minimal ignition energy, heightening the risk of pre-ignition, flashback, and explosion, especially in tight or inadequately ventilated spaces. Hydrogen possesses an extensive flammability range in air (4–75%), rendering it more susceptible to inadvertent ignite. Moreover, hydrogen fires are almost imperceptible, complicating detection and monitoring without specialized instruments. Material compatibility is a significant concern, as hydrogen can induce metallic embrittlement, resulting in long-term durability challenges in combustion systems. The enhanced diffusivity and reduced density of hydrogen hamper its storage and transportation, necessitating sophisticated confinement systems. These issues require new combustion system designs and stringent safety regulations to efficiently and securely utilize hydrogen as a fuel.

Designing burners, particularly for contemporary low-emission and alternative fuel applications, presents numerous intricate issues. A critical challenge is attaining stable and efficient combustion while reducing pollutant emissions, including NO_x, CO, and unburned hydrocarbons. This necessitates meticulous regulation of fuel-air amalgamation, flame stability, and thermal distribution. The utilization of alternative fuels, such as hydrogen or ammonia, necessitates the design of specialized burner geometries and materials due to their distinct combustion characteristics, including elevated flame speed and reduced ignition temperature. This would lead to complexity in flame stabilization in burners at various scales. Also, due to the high diffusivity of H2, hydrogen combustion is prone to instabilities, which can lead to the failure of combustion systems. Consequently, burner design must reconcile performance, efficiency, durability, and safety, frequently necessitating iterative modeling, simulation, and experimental validation.

An integrated, multidisciplinary approach that combines techno-economic analysis, material science, chemical engineering, computational physics, and data-driven approaches will be key to unlocking the full potential of hydrogen as a clean energy carrier.

3.5 Limited Data Accessibility

A key hurdle in realizing India's complete research and innovation potential in the hydrogen sector is the absence of open-access data platforms that comprehensively catalogue hydrogen startups, ongoing projects, research activities, and industry players. The lack of transparent, accessible data creates a fragmented ecosystem where policymakers, investors, academic researchers, and industry stakeholders operate with incomplete or outdated information.

Since green hydrogen is still an emerging industry, early-stage innovations often depend heavily on cross-sector collaboration, technology validation, and market entry support. India's hydrogen sector lacks a centralized repository detailing critical parameters such as startup profiles, technology readiness levels (TRLs), pilot project results, manufacturing capabilities, safety testing data, and funding status. Without such infrastructure, startups face difficulties building credibility, researchers struggle to identify industry needs, and financiers cannot adequately assess project risk or viability.

The absence of systematically organized and verified data amplifies market asymmetry, favors established players and marginalizes smaller innovators who could otherwise contribute significantly to India's technological self-reliance. Addressing this gap should, therefore, be a strategic priority.

The Ministry of New and Renewable Energy, Government of India, maintains a database of hydrogen projects, policy documents, campaign events, personnel directory, regulations, and standards. The existing database needs to expand its scope by including information about hydrogen startups to strengthen the research and technology development network.

A national hydrogen data platform, curated with input from government agencies, industry associations, academic institutions, and independent validators, could be a vital enabler of technology and industry readiness. Such a platform could track metrics related to production capacity, electrolyzer deployments, safety test results, funding rounds, pilot project outcomes, and R&D collaborations.

Regular updates and validation mechanisms would ensure data credibility and utility. Promoting open-access, verifiable, and standardized data dissemination will lower barriers to indigenous technology development, enhance investor confidence, improve risk assessments, and create a more competitive, innovation-driven hydrogen ecosystem.

04 Recommendations for Long-term Roadmap

4.1 Policy and Regulatory Interventions

Policy and regulatory interventions should promote multiple decarbonization pathways tailored to the specific needs of different sectors and use cases. To create a robust market for green hydrogen, introducing Green Hydrogen Purchase Obligations (GHPOs) can ensure a guaranteed off-take from industries, similar to Renewable Purchase Obligations (RPOs) in the solar sector. Accelerating the standardization of electrolyzers will enable domestic manufacturers to scale up production while ensuring efficiency and safety benchmarks. A well-defined sectoral green hydrogen taxonomy will clarify classifications, certifications, and incentives, guiding industry adoption and regulatory compliance.

4.2 Infrastructure and Market Development

Infrastructure and market development are crucial to ensuring the smooth deployment of green hydrogen across various sectors. A centralized government portal should be created to disseminate real-time information on projects related to green hydrogen, reducing information asymmetry.

Establishing hydrogen corridors with dedicated pipelines and refueling stations will enhance connectivity and support mobility applications.

Accelerating the disbursement of funds for Hydrogen Valley projects is essential to fostering regional hydrogen ecosystems. Transparent timelines, accountability mechanisms, and simplified fund release protocols can be adopted.

Decentralized hydrogen production infrastructure located near consumption centers can lower transportation costs and strengthen energy security, supporting the growth of a resilient hydrogen market.

4.3 Financing and Investment Acceleration

Financing and investment acceleration require targeted incentives and risk-mitigation strategies to attract capital. Expanding Production-Linked Incentives (PLI) to include micro, small, and medium enterprises (MSMEs) engaged in green hydrogen technology development will ensure broader participation in the sector.

4.4 Strengthening Research and Industry-Academia Collaboration

Promoting open-access, verifiable, and standardized data dissemination by developing novel data platforms that provide reliable information on green hydrogen production, consumption, infrastructure, and market trends.

Strengthening research and industry-academia collaboration is vital to driving innovation and workforce readiness. Creating interdisciplinary R&D centers focused on green hydrogen technologies will promote synergies between material science, engineering, and policy research.

Incentivizing outcome-based research that aligns with industry needs by government agencies, funding bodies, and academic institutions will ensure that academic projects contribute to real-world applications rather than remaining purely theoretical.

Launching national-level skill development programs will prepare a workforce with expertise in hydrogen production technologies, electrolyzer operation, safety management, pipeline and storage system maintenance, and fuel cell applications, fostering a competitive domestic industry in the global hydrogen economy.

05 Conclusion

India holds strategic advantages such as abundant, low-cost renewables, cost-competitive hydrogen production, a strategic export location, and established industrial clusters for promoting green hydrogen compared to the rest of the world. Successfully adopting green hydrogen in India requires a holistic approach integrating policy reforms, infrastructure development, financial mechanisms, and industry-academia collaboration. While significant strides have been made in positioning green hydrogen as a key pillar of India's energy transition, critical challenges remain in scaling up production, ensuring economic viability, and fostering widespread industry adoption. Addressing these barriers will require coordinated efforts from policymakers, financial institutions, researchers, and industry stakeholders.

Developing a robust green hydrogen ecosystem demands government efforts beyond supply-centric policymaking to a demand-driven approach. Establishing clear mandates, such as Green Hydrogen Purchase Obligations (GHPOs), will create a stable market and encourage investments. Standardization and certification frameworks must be expedited to enhance India's participation in global hydrogen trade, reduce information asymmetry, and build investor confidence. Simultaneously, infrastructure gaps including dedicated hydrogen pipelines, refueling stations, and storage facilities must be addressed to ensure seamless integration of hydrogen across sectors.

Investment challenges remain a significant bottleneck, with financial institutions grappling with risk assessment and the long payback periods associated with green hydrogen projects. De-risking mechanisms such as blended finance models, sovereign guarantees, and targeted incentives for MSMEs will be crucial in mobilizing capital. Furthermore, shifting from a purely loan-based financing model to one incorporating grants and strategic public-sector support will create a more sustainable investment landscape.

The workshop identified five key focus areas financing and investment landscape, challenges of funding timelines, testing and standards, research and development, and limited data accessibility that require strategic attention. Addressing these areas through well-designed interventions will be essential to support the effective and timely implementation of India's green hydrogen ambitions.

Industry-academia collaboration must be strengthened to bridge the gap between research and commercialization. Encouraging problem-centric and outcome-based research, fostering interdisciplinary collaborations, and redefining academic performance metrics to align with industry needs will drive meaningful innovation. Moreover, dedicated skill development programs must be launched to create a workforce capable of supporting the entire green hydrogen value chain, from production and storage to transportation and utilization.

India has a unique opportunity to establish itself as a global leader in green hydrogen, leveraging its vast renewable energy resources and growing industrial demand. However, this requires swift and decisive action across multiple fronts. By fostering a well-coordinated ecosystem where policy, finance, technology, and research converge India can accelerate its green hydrogen transition, enhance energy security, and contribute meaningfully to global decarbonization efforts.

Annexure A: Government of India Initiatives

India's green hydrogen transition is actively shaped by government-led initiatives to foster policy support, infrastructure development, and market creation. Recognizing the opportunities and challenges in scaling up green hydrogen, the Government of India has introduced targeted policies and regulatory frameworks to accelerate deployment. In parallel, state governments are formulating strategies to complement and strengthen central policies, ensuring a more localized and practical implementation approach. This section outlines the key government initiatives driving India's green hydrogen agenda.

National Green Hydrogen Mission

In January 2023, the Ministry of New and Renewable Energy (MNRE) launched the National Green Hydrogen Mission (NGHM), a cornerstone of India's clean energy transition strategy (Ministry of New & Renewable Energy, 2023). The Mission aims to establish India as a global hub for green hydrogen production, utilization, and export given that India currently consumes around 5 million metric tonnes (MMT) of hydrogen annually primarily for industrial applications such as petroleum refining, ammonia production, methanol synthesis, and metal processing the Mission seeks to replace fossil fuel-based hydrogen with green hydrogen, thereby reducing carbon emissions and enhancing energy security.

The Mission's primary objective is to establish a robust green hydrogen ecosystem that supports India's ambitions for self-reliance (Aatmanirbhar Bharat) in clean energy while contributing to global decarbonization efforts. By 2030, India aims to achieve an annual green hydrogen production capacity of at least 5 MMT, with the potential to scale up to 10 MMT depending on market growth and export opportunities. This initiative is expected to significantly decarbonize the economy, reduce dependence on fossil fuel imports, and enable India to become a leader in green hydrogen technology and manufacturing.

The Mission strategy accordingly comprises interventions for: Demand creation can be achieved by producing Green Hydrogen in India, which is competitive for exports and domestic consumption. Addressing supply-side constraints through an incentive framework, Builds an enabling ecosystem to support scaling and development.

To achieve these objectives, the Mission focuses on utilizing multi-pronged approaches, including:

Fossil Fuel Substitution: Replacing grey hydrogen with green hydrogen in ammonia production, petroleum refining, and other industrial processes.

Sectoral Expansion: Integrating green hydrogen in emerging applications such as city gas distribution, steel production, mobility, shipping, and aviation, using green hydrogen-derived synthetic fuels like green ammonia and green methanol.

Technology Leadership: Strengthening India's manufacturing capabilities in electrolyzers and other critical hydrogen-related technologies.

Phased Implementation: Given the nascent stage of the green hydrogen sector, the Mission is structured in phases. The initial phase prioritizes deployment in industries already using hydrogen alongside developing an ecosystem for research and development (R&D), regulations, and pilot projects. The later phase will expand green hydrogen applications to new sectors, facilitating large-scale adoption.

The Mission encompasses several financial incentive schemes and policy measures to support the green hydrogen ecosystem:

1. Strategic Interventions for Green Hydrogen Transition (SIGHT) Programme:
Component I: Provides incentives for domestic manufacturing of electrolyzers to enhance production capacity and reduce costs.
Component II: Offers incentives for the production of green hydrogen, aiming to make it cost-competitive with fossil fuel-based alternatives. The total outlay for the SIGHT Programme is ₹17,490 crore up to 2029-30.

2. Pilot Projects:
Allocated ₹1,466 crore for pilot projects in sectors like steel, mobility, and shipping to demonstrate the viability of green hydrogen applications. For instance, ₹208 crore has been approved for five pilot projects involving 37 vehicles and nine hydrogen refueling stations across various routes in India.

3. Green Hydrogen Hubs:
An outlay of ₹400 crore is designated for developing regions capable of supporting large-scale production and/or utilization of hydrogen, termed Green Hydrogen Hubs.

4. Green Hydrogen Certification Scheme (GHCI):
Launched to certify the green credentials of hydrogen produced, ensuring transparency and enabling producers to claim carbon credits under India's Carbon Credit Trading Scheme. The scheme sets a threshold of 2 kg of CO_2 equivalent per kg of hydrogen produced, averaged over 12 months.

5. International Collaborations
MNRE, in partnership with the European Union, has launched a joint call for proposals with a funding commitment of up to ₹90 crore for Indian participants. The initiative focuses on converting biogenic waste into renewable hydrogen, promoting innovative biochemical and thermochemical technologies.

6. Policy Measures
Waiver of interstate transmission charges for renewable energy used in green hydrogen production.
Facilitate renewable energy banking and time-bound grant of open access and connectivity for green hydrogen projects.

The phased approach of the Mission will enable the taking up of foundational activities like the regulatory framework and pilot projects while also creating demand and early deployment. Later phases will build on these activities and undertake green initiatives in new sectors of the economy. The Mission is expected to achieve the following outcomes:

India's Green Hydrogen production capacity is likely to reach at least 5 MMT per annum, with an associated renewable energy capacity addition of about 125 GW. With the growth of export markets and international partnerships, the production capacity could be scaled to 10 MMT annually.

The production capacity targeted by 2030 will likely leverage over Rs. 8 lakh crore in total investments and create over 6 lakh jobs.

Due to the various Green Hydrogen initiatives under the Mission, nearly 50 MMT per annum of CO2 emissions are expected to be averted in identified industrial sectors, including steel, shipping, energy storage, and long haul mobility.

By addressing these priorities, the National Green Hydrogen Mission is expected to bolster India's clean energy ambitions and contribute to global efforts in transitioning towards a low-carbon economy.

State-level Policies

While the central government has set the foundation for India's green hydrogen (GH_2) transition, state governments are actively formulating policies to supplement national initiatives and attract investments. State-level policies complement the National Green Hydrogen Mission by addressing region-specific challenges and opportunities.

States are positioning themselves as key players in India's green hydrogen transition by providing incentives, promoting industrial applications, and investing in research and infrastructure.

Several states have announced targeted strategies to promote green hydrogen production, infrastructure development, and sectoral adoption. These policies focus on leveraging regional strengths, ensuring energy security, and establishing India as a global leader in GH_2 production.

State	Policy Highlights	Focus Areas	Key Targets / Numbers	Current Gaps / Challenges
Andhra Pradesh	Green Hydrogen and Green Ammonia Policy 2023.	Green ammonia exports, port-based hydrogen hubs.	The target of 0.5 MMT green hydrogen production by 2030.	Lack of clear demand mandates and off-taker agreements.
Gujarat	Renewable Energy Policy 2023 with hydrogen promotion emphasis.	Large-scale electrolyzer manufacturing, hydrogen hubs.	Plans to produce 1 MMT green hydrogen by 2030.	Specific adoption incentives and R&D support are evolving.
Maharashtra	Draft Green Hydrogen Policy (under consultation in 2024).	Industrial decarbonization, mobility applications.	Indicative target of ~0.25–0.3 MMT by 2030 (draft).	Draft not finalized; financial incentives unclear.
Odisha	Green Hydrogen and Green Ammonia Policy 2023.	Green hydrogen hubs near steel plants and ports.	The target of ~0.5 MMT green hydrogen production by 2030.	Early-stage infrastructure development; policy execution pace slow.
Rajasthan	Renewable Energy Policy 2022 encouraging hydrogen clusters.	Solar-powered electrolyzer deployment, export hubs.	Target to become a leading exporter; expected 1–1.5 MMT capacity by 2030.	Storage, transport, and domestic demand frameworks are missing.
Uttar Pradesh	Draft State Hydrogen Policy focusing on industrial clusters (early 2024 draft).	Fertilizers, refineries, transport fuel.	No explicit MMT target yet; under formulation.	Draft stage; lacks operational programs and pilots.
West Bengal	Preliminary stage policy announcement for hydrogen hubs.	Mobility, steel sector pilots.	No official targets declared yet.	Policy framework and incentives pending announcement.

Note: This table is based on the latest announcements as of 2024; some figures for draft policies are indicative projections until official policies are released.

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