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INSIGHTS & OPINION

GREEN HYDROGEN

Insights on Realizing its Inclusion and Impact in India

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Citation

Kumar, S., Singh, H., Verma, G., Deutkar, S., Bhatt, U., Wicmandy, M., Ranjan, R., Dasgupta, P., Stanislaus, M.S., Guduru, R.K., Kumar, R., Kumar, S. and Bera, A., 2025. *Green Hydrogen: Insights on realizing its inclusion and impact in India*. RINOLYST.

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SciGlyph Exploration Private Limited,
Patna, Bihar, India
www.rinolyst.com

SEPTEMBER 2025

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Acknowledgement

This report reflects the insights of dedicated contributors working at the intersection of climate resilience and sustainable development, supported by RINOLYST's commitment to advancing evidence-based solutions through in-house and collaborative research. **We sincerely thank all contributors whose expertise has shaped this study.**

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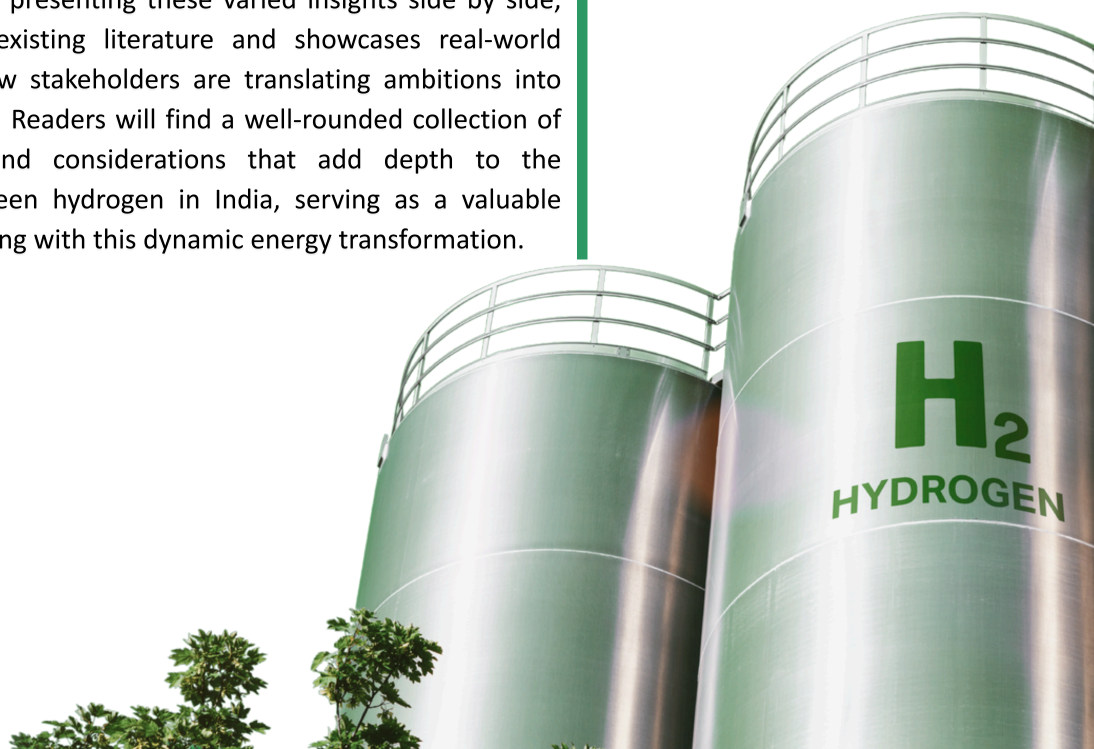
PURPOSE

India's green hydrogen landscape is evolving swiftly under the National Green Hydrogen Mission, with diverse initiatives spanning refineries, fertilizers, steel mills, mobility solutions, power systems, and novel applications in agriculture and urban resilience. RINOLYST invited professionals from research institutions, manufacturing companies, energy utilities, policy bodies, and consulting firms to contribute their sectoral insights, challenges, and recommendations across eight critical dimensions of green hydrogen development. This report gathers firsthand perspectives from these practitioners, who are each engaged directly or indirectly in India's green hydrogen ecosystem, to enrich understanding of the sector's evolution and highlight practical viewpoints on market transparency, inclusive development, value chain optimization, sectoral integration, innovation pathways, investment strategies, regulatory enablement, and phased implementation. By presenting these varied insights side by side, the report complements existing literature and showcases real-world experiences, illustrating how stakeholders are translating ambitions into ongoing projects and pilots. Readers will find a well-rounded collection of observations, examples, and considerations that add depth to the conversation on scaling green hydrogen in India, serving as a valuable reference for anyone engaging with this dynamic energy transformation.



EXECUTIVE SUMMARY

India's green hydrogen journey is advancing through strong early initiatives across sectors under the National Green Hydrogen Mission, targeting 5 MMT annual production by 2030, alongside goals to create 600,000 jobs, reduce greenhouse gas emissions (GHG) by 50 MMT annually, and save ₹1 lakh crore in fossil fuel imports. This report provides an overview of this evolving landscape, highlighting initiatives and development across key sectors and presenting a multi-faceted perspective through the collection of opinions on various aspects of the green hydrogen ecosystems to connect its entire value chain.

India’s push is cohering across connected fronts: The refinery sector has floated tenders for 42,000 tonnes per annum of green hydrogen and planned projects worth approximately ₹2 trillion, signaling a clear shift from grey to green in the near future. In fertilizers, competitive auctions have discovered record-low green ammonia tariffs near ₹50/kg, narrowing the cost gap with conventional supply and signaling real delivery potential under recent schemes. In steel, a national green steel taxonomy and funded pilots are transforming trials into process changes, creating a bridge from incremental substitutions to deeper, long-term decarbonization pathways. Mobility is moving from concept to early operations, with fuel-cell buses, heavy trucks, heritage-route trains, and production and refuelling initiatives at ports. Complementing this, microgrids and utilities powered by electrolyzers, fuel cells, and blended gas demonstrate how decentralized models can extend clean energy access to underserved areas. Efforts in electrolyser manufacturing, pilot projects, and strategic partnerships are driving a transitioning energy economy focused on reducing carbon emissions and promoting sustainable growth. However, nationwide pipeline analysis shows that announced volumes already surpass the 2030 goal, with most capacity clustered in coastal and renewable-rich states and only a small fraction operational; underscoring the urgency to strengthen siting, enabling infrastructure, logistics, and bankable offtake so plans convert to projects at pace. Despite multiple promising pilots and demonstrations, the central challenge remains to scale decisively from early activity to substantial commercial operations across regions.

Addressing these challenges requires diverse perspectives to illuminate practical pathways for technology deployment, policy alignment, infrastructure development, and market mechanisms that can accelerate the transition from promising pilots to scalable commercial operations across India's green hydrogen value chain.

The first set of opinions calls the urgent need for a robust and transparent market intelligence system. Accurate, granular data on demand across sectors and regions, as well as detailed visibility into supply, electrolyzer capacity, and renewable energy integration, are essential for guiding investment decisions and optimizing project siting. Coupled with this, the establishment of a dedicated green hydrogen exchange with transparent price discovery mechanisms and standardized contract structures is vital to fostering liquidity and investor confidence. Furthermore, a centralized market intelligence unit is proposed to ensure data integrity, perform insightful market analyses, and disseminate actionable information, thereby reducing uncertainty and accelerating growth.

Further, the report highlights the importance of inclusive market development to empower smaller players and encourage widespread adoption. Innovative business models that combine centralized production with decentralized marketing and last-mile delivery can enhance equitable access, particularly for micro, small, and medium enterprises. Equally important is the democratization of electrolyzer access through standardized modular units, aggregated procurement, and financing solutions, which will lower barriers for smaller producers and augment supply diversity. Localized demand aggregation through digital platforms and strategic cluster development is identified as a key strategy to ensure reliable off-take and reduce transportation costs.

Optimizing the value chain to reduce costs remains a significant focus. Developing efficient hydrogen transportation and distribution infrastructure, including dedicated pipelines, specialized carriers, and last-mile networks, alongside scalable and diverse storage solutions tailored to different geographic and application needs will underpin economic viability. The report recognizes the complexities in balancing safety, cost, and flexibility, advocating for a layered storage strategy encompassing gaseous, liquid, chemical, and underground options.

Beyond industrial applications, green hydrogen offers transformative socio-economic and environmental benefits. It promises substantial job creation across the production ecosystem and priority sectors, enhances public health through pollution reduction, and fosters circular economy practices such as carbon capture utilization and resource recycling. Its role extends to rural and semi-urban energy access, powering decentralized utilities, clean cooking, and climate-smart agriculture, as well as bolstering urban resilience by ensuring reliable power and emergency services during climate disruptions.

A vibrant innovation ecosystem is highlighted as foundational for long-term success. Tailored support for research institutions, startups, and industry collaboration is critical to bridging the lab-to-market gap. Aligning R&D priorities with real-time market needs, strong public-private partnerships, and strategic investments will accelerate technology commercialization and build indigenous capabilities in electrolyzers, fuel cells, and hydrogen logistics.

Investment mobilization and financial de-risking are emphasized as key enablers to attract the substantial capital required. Innovative financing models, blended instruments, and enhancing market transparency will build investor trust and unlock resources for distributed and pioneering projects. The importance of a coherent policy and regulatory environment is also underlined, with adaptive frameworks enabling open power access, certification systems, and streamlined clearances to reduce project risks and harmonize regulations across states.

Finally, the report outlines a phased, actionable roadmap for implementation. It prioritizes building early green hydrogen hubs near industrial clusters, scaling pilot projects with viability support, and fostering competitive bidding to bring costs down. Strategic leveraging of port infrastructure and international partnerships aims to position India as a future global exporter, capturing a significant share of the emerging green hydrogen market. Progress depends on continued cross-sector collaboration, transparent data systems, and capacity building to convert ambitious plans into measurable, sustainable outcomes that contribute to India's climate goals and energy security.

Delivering this vision now hinges on coordinated action that aligns incentives, streamlines clearances, and closes the lab-to-market gap through incubation and R&D support, while blended finance, viability-gap funding, guarantees, and strategic partnerships unlock capital, enable technology transfer, and build export readiness. With this integrated push across infrastructure, finance, policy, and innovation, India can move from pilots to scale, meet domestic energy and climate goals, and position itself as a reliable global supplier of green hydrogen and derivatives.

SECTOR-WISE

INITIATIVES & DEVELOPMENTS

Refinery & Petrochemicals

The refining and petrochemicals sector is a pivotal focus for green hydrogen deployment in India, driven by the imperative to decarbonize operations that heavily rely on fossil-derived hydrogen. Petroleum refining, in particular, is a key area for government-backed green hydrogen adoption to replace the approximately 5 MMT of grey hydrogen consumed annually in India, with about 99% of this utilized in refining and for manufacturing ammonia for fertilizers.[1] The strategic placement of green hydrogen production facilities relative to these demand centres is paramount for optimizing the overall value chain. India is planning green hydrogen projects worth approximately ₹2 trillion ($23 billion), with state-owned oil refineries leading the charge by floating tenders for 42,000 TPA (tonnes per year) of green hydrogen production, and an additional 128 tenders anticipated based on the outcome.[1,2] IOCL at its Panipat refinery complex buildings India's largest green hydrogen plant with a capacity of 10,000 TPA, expected to operate by end of 2027.[2] Such significant investment underscores the sector's commitment to transitioning towards greener operations.

Initiatives in this sector demonstrate a clear progression towards integrating green hydrogen. As early as December 2021, Bharat Petroleum Corporation Limited (BPCL) began collaborating with the Bhabha Atomic Research Centre (BARC) to scale up indigenous Alkaline Electrolyser technology, specifically aiming to replace the grey hydrogen used in its refineries for processes like desulfurization.[3] Expanding on this, BPCL has set an ambitious target to produce 30 KTPA of green hydrogen in its refineries by 2030, initiating projects such as a 5 MW green hydrogen plant at its Bina Refinery and tendering for 5 KTPA supply across its Mumbai, Kochi, and Bina refineries on a Build-Own-Operate (BOO) basis.[4,5] As a part of the initiatives for the green hydrogen production by domestic oil refineries, four R&D or demo plants have already been commissioned by state-owned entities including Indian Oil Corp (IOC), GAIL India, Hindustan Petroleum Corp (HPCL), and BPCL, with nine more under construction.[2]

Concurrently, other major energy entities are making significant strides. In April 2022, Indian Oil Corporation Ltd. (expertise in petroleum refining) formed a tripartite joint venture with Larsen & Toubro (strong credentials in designing, executing, and delivering EPC projects) and ReNew Power (offering and developing utility-scale renewable energy solutions) to advance the green hydrogen business, with an initial focus on projects at IndianOil's Mathura and Panipat refineries.[6] IndianOil subsequently invited global tenders in August 2023 for a 10 KTPA green hydrogen plant (expected to operate round-the-clock and intended to produce 1,250 kg of green hydrogen per hour) at its Panipat refinery, aiming to integrate it with the existing hydrogen network for continuous operation.[7] This landmark project was finalized in May 2025, with L&T Energy GreenTech securing the contract to develop and operate the 10 KTPA facility at Panipat under a 25-year supply agreement, slated for commissioning by December 2027.[8,9] IndianOil aims to convert 50% of its refinery hydrogen use to green by 2030, amounting to 350,000 mtpa of green hydrogen within its refineries.[10]

Beyond these, other public sector undertakings are exploring green hydrogen applications within their refining and petrochemical operations. In May 2023, NTPC Green Energy Limited (NGEL) signed an MoU with HPCL Mittal Energy Limited (HMEL), an integrated refining and petrochemical company, to explore green hydrogen and its derivatives (Green Ammonia & Green Methanol) for HMEL's Guru Gobind Singh Refinery in Bathinda.[11] Similarly, NGEL and Numaligarh

Refinery Limited (NRL) entered a non-binding MoU in the August 2023 to investigate partnerships in green chemicals, including a proposed bamboo-based bio-refinery.[12] Oil and Natural Gas Corporation Ltd. (ONGC) is undertaking a pre-feasibility study for a green hydrogen plant in Mangaluru to serve the energy needs of Mangalore Refinery and Petrochemicals Ltd. (MRPL).[13] GAIL (India) Limited also commissioned its first Green Hydrogen Plant at Vijaipur in May 2024, a 4.3 TPD (10 MW PEM Electrolyser) facility, with the hydrogen initially intended for captive use in existing plant processes.[14] later on, in 2025 GAIL signed MOU with Accelera™ by Cummins (Cummins Inc.) to explore opportunities, applications and adoption of hydrogen in various sectors.[15] As part of energy transition, GAIL is on course to set up 26 plants across India in the next 3-4 years.[15] HPCL has set a target for more than 9,670 TPA green hydrogen by 2029-2030; out of which a 370 TPA Green Hydrogen Plant has already been commissioned and 5,000 TPA is underway at Visakh Refinery (Andhra Pradesh) along with 4,300 TPA Green Hydrogen Project at HRRL.[16,17,18,19] These concerted efforts underscore a strategic national drive to integrate green hydrogen into the refining and petrochemicals sector, aiming for substantial decarbonization and enhanced energy independence. The proximity of green hydrogen production to these industrial demand centres is a critical factor for the success of on-site stand-alone projects, as the costs associated with transporting hydrogen over long distances can significantly erode the economic benefits of local production and necessitate extensive, expensive infrastructure for storage and distribution.

Ammonia and Fertilizer

India's journey toward decarbonizing its ammonia and fertilizer sectors through green hydrogen adoption has evolved through strategic partnerships and technological innovations, and is gaining serious momentum.[20] This is a critical transition, as the country's current hydrogen demand of 17–19 million tonnes of ammonia per year, largely (more than 50%) for fertilizer production, is mostly met by fossil fuels (imported natural gas), leading to substantial carbon emissions.[21] The central government's Green Hydrogen policy, laid the groundwork for this shift, followed by a flurry of strategic partnerships and projects.[22]

Started in 2020-2021, India's green ammonia landscape was nascent, but initiatives were underway to leverage renewable energy for ammonia production, primarily for fertilizer and fuel applications.[23] Parallelly, ACME commissioned (Operational since 2021) world's first fully integrated green ammonia plant at Bikaner, Rajasthan, with a project capacity of 5 MTPD NH_3 and projected to save approximately 4400 tons of CO_2 emissions annually.[24] At the same time NTPC was exploring the sector's green hydrogen journey by exploring green ammonia production to meet the government's planned mandate for green hydrogen usage in fertilizer and refinery sectors.[25] This foundation led to concrete partnerships in July 2022, when NTPC RE Limited (NTPC REL) signed MoUs with both National Fertilizers Limited (NFL) for supplying 90 MW renewable power and producing 50 tonnes per day (TPD) of green ammonia, and Gujarat Alkalies and Chemicals Limited (GACL) for 75 TPD green methanol and 35 TPD green ammonia production.[26,27] Simultaneously in July 2022, ONGC and Greenko (ZeroC) established a joint venture to develop a 1 MMTPA green ammonia production facility, powered by 1.3 GW of green hydrogen for export, leveraging Greenko's pumped hydro storage platform to ensure a round-the-clock supply of renewable energy.[28] Along with the pilot facility at Bikaner, Rajasthan, ACME group involved in a planned investments of Rs 1.5 trillion over seven years for projects in Tamil Nadu (~1.2 MMTPA), Karnataka (~1.1 MMTPA), and Odisha (~1.2 MMTPA).[29,30,31,32,33] For the Odisha

(Gopalpur) project, ACME and IHI Corporation (a Japanese integrated heavy industry group) signed an offtake term sheet for supply of green ammonia from Odisha, India to Japan, and the first production likely within 2027.[32] The Adani Group also formed a joint venture with Kowa Holdings Asia Pte Ltd, Singapore to market green hydrogen and its derivatives in Japan, Taiwan and Hawaii.[34] The Adani project, led by Adani New Industries Limited (ANIL), aims to produce 1 MMTPA (and later up to 3 MMTPA in the next 10 years) of green hydrogen in Gujrat, with the first phase expected to begin by FY2027.[34]

The progress has been complemented by state-level policy support as seen in the Andhra Pradesh, targeted Green Hydrogen production up to the capacity of 0.5 MTPA or Green Ammonia production up to the capacity of 2.0 MTPA in the next five years.[35] Other states including Punjab (100 KTPA) and Maharashtra (500 KPTA) Green Hydrogen Policy, also in the way to fulfil the committed targets of green hydrogen/green ammonia production by 2030 and offers comprehensive incentives.[36,37] Karnataka may take advantage of utilizing more than 50% of its electricity generation being based on renewables for generation of green hydrogen and ammonia.[38] The companies like JSW (Green Hydrogen) ACME Group, Avaada, ReNew Power, PETRONAS, O2 Power and ABC Cleantech have already announced their plans for green hydrogen for its end-use as green ammonia (more than 5 MTPA) in Karnataka.[38]

Major commitments emerged in 2024-2025, including ACME's (with IHI) 1.2 MMTPA Green Ammonia project at Gopalpur, Odisha, NTPC Green Energy's (NGEL) MoU (Jan 2024) with Maharashtra for up to 1 million tonnes annual capacity with ₹80,000 crores investment, Adani Energy Solutions Ltd. (AESL) transmission project (won in 2025) in Gujarat to supply green electrons for a green hydrogen/ammonia manufacturing hub in Mundra, AM Green (signed a non-binding MoU with Coal India Limited (CIL) in May 2025) for CIL to supply 4.5 GW of wind and solar power for green ammonia production.[31,39,40,41] AM Green Energy is targeting a production capacity of around 5 million tons per year of green ammonia by 2030 from multiple plants distributed across the country, including Andhra Pradesh (Kakinada), Tamil Nadu (Tuticorin), Himachal Pradesh (UNA), and Gujarat (Kandla).[41,42] Parallelly, the sector witnessed significant policy momentum in 2024 when the government enhanced the SIGHT Programme allocation for fertilizer sector from 5.5 lakh tonnes to 7.5 lakh tonnes per annum of green ammonia.[43] This rapid industrial scale-up is underpinned by government initiatives like the SECI tender in June 2025, seeking 724,000 tonnes of green ammonia annually for 13 fertilizer plants under the SIGHT scheme.[21]

The sector achieved commercial breakthroughs in August 2025 through SECI's competitive auctions under the SIGHT scheme.[44] The record-low prices (discovered or fixed-delivery price) of ₹55.75/kg (ACME), ₹53.50/kg (Onix Renewable), ₹53.05/kg (SCC Infrastructure), ₹52.25/kg (Oriana Power), ₹51.8/kg (NREL), and ₹50.75/kg (Jakson Green) for green ammonia, a substantial drop from the ₹100.28/kg seen in 2024, brought it close to the cost of conventional ammonia, thus confirming economic viability and setting the stage for wide-scale adoption in India.[45,46,47,48]

Iron and Steel

The steel sector, responsible for roughly 12% of the country's CO_2 emissions and contributing nearly 2% of India's GDP, has rapidly expanded over the last two decades to become the second-largest producer globally.[49] India's steel accounts an average emissions intensity of 2.54 tonnes of

CO_2 per tonne of crude steel (t-CO_2/tcs), which is significantly higher than the global average of ~1.91.[49] With around 98 KGs per capita steel consumption that is well below the global average (~215 KGs), the industry is poised for substantial growth (160 KGs per capita consumption by 2030), making its decarbonization a critical and urgent priority.[50,51] With a target of reducing the average emission intensity to 2.2 t-CO_2/tcs by 2030, green steel shall be defined through greenness star-ratings or levels (distributed emission intensity between 1.6 to 2.2).[52] The reduction in emission intensity while increasing the steel production capacity (179.5 MT in 2024 to 300 MT by 2030-31) required deep decarbonization of steel and iron sector. This is particularly difficult because conventional ironmaking is a hard-to-abate process that is heavily dependent on coal (93% of the total iron and 75% of total steel production).[49] The sector alone consumes a significant 20-25% of the country's total industrial energy, with over 85% of that consumption coming directly from coal.[49,53,]

Shifting to green hydrogen, produced using renewable energy, is expensive, and its current cost (4-6 $/kg) is notably higher than that of the fossil fuels it would replace.[49] Furthermore, the necessary infrastructure for producing, storing, and transporting green hydrogen is still in its early stages of development. There is also a geographical challenge, as major steel plants are often located (mostly in the eastern and western parts of the country) far from the renewable energy sources that would power hydrogen production. Therefore, hydrogen can be provided to the steel plants either through pipelines or the plants can opt for in-house production. The relatively young average age of India's furnaces, also presents a barrier, as these assets have a long operational life and would require significant capital to retrofit or replace.[54] Therefore, decarbonizing steel sector through the energy efficiency, renewable energy, and CCUS to meet their NetZero targets (varying from 2035-2070) is preferable at the moment.

On the ground, major steel players are leading the transition with a series of distinct projects. The Kalyani Group, a pioneer in green steel using scrap and renewable energy, is actively exploring green hydrogen, while highlighting the critical need for costs to drop to around $1-2 per kg to achieve commercial viability.[55] Along with utilizing around 2.61 Billion Units (BU) of renewable energy in FY25, Vedanta Limited (with IIT, Bombay) is developing cost-effective technology for producing green steel using hydrogen, targeting significant carbon footprint reduction in Iron and Steel space.[56,57] Tata Steel achieved a global first by successfully trialing a continuous hydrogen gas injection in a blast furnace, which resulted in a 10% reduction in coke consumption and a 7-10% decrease in CO_2 emissions.[58] This demonstrates the potential for incremental decarbonization. Hygenco builds, owns, and operates multiple green hydrogen facilities across the country, including Haryana and Maharashtra. Jindal Stainless Limited and Hygenco have launched "Project Steel One," a commercial-scale initiative where green hydrogen will replace ammonia in the annealing process at Jindal's Hisar facility, with a goal of reducing annual CO_2 emissions by ~2,700 tonnes.[59,60] This will be done through the India's first longterm off-take green hydrogen plant (company premises, Hisar, Haryana) with a production capacity of 78 tonnes per year of green hydrogen.[49] JSW Steel is setting up a 25 MW green hydrogen facility in Vijayanagar, Karnataka (pilot, by 2025), which will produce 3,600 tonnes of hydrogen per year for use in their DRI (Direct Reduced Iron) process.[61,] Similarly, ArcelorMittal Nippon Steel India (Hazira, Gujarat AM/NS Essar Steel India) is focusing on generating its own clean power with a large wind-solar hybrid plant to reduce emissions by 1.5 million tonnes annually.[62] Moreover, Maharashtra government has signed an MoU (for green hydrogen projects) with ArcelorMittal Nippon Steel India for an investment worth ₹40,000 crore in Maharashtra, India to set up a green steel plant with a capacity of 6 million tonnes per annum.[63]

Based on the recent initiatives it seems green hydrogen utilization in steel sector is in very early stage and still challenging. Recognizing key challenges, the Indian government has allocated ₹456 crore (until FY 2029-30) specifically for steel sector pilot projects and also developed a comprehensive green steel taxonomy.[52,64] The government has sanctioned various pilot projects in the steel sector (under green hydrogen mission) including Matrix Gas and Renewables Ltd (50 TPD), Simplex Castings Ltd (40 TPD), and SAIL (3200 TPD).[65,66] Such pilot projects will focus on complete hydrogen utilization in vertical shaft furnace for DRI, partial substitution of natural gas, and injection into existing blast furnaces to decrease coal and coke consumption.[66] However, the journey to green steel in India is a strategic, phased process that requires significant investment. The primary focus is to reduce the cost of green hydrogen and build out the necessary infrastructure, with the ultimate aim of transitioning from pilot projects to a full-scale, coal-free industry.

Mobility & Transportation

The integration of green hydrogen into India's mobility and transportation sectors is a key component of the country's decarbonization strategy, anchored by the National Green Hydrogen Mission. This mission, with an outlay of ₹496 crore for mobility pilot projects up to 2025-26, has initiated a wide range of strategic and commercial developments across different modes of transport.[67]

India is making a significant push to decarbonize its road transport sector, with a national goal of deploying over 1,000 hydrogen-powered buses and trucks by 2030.[68] A number of pilot projects are underway, supported by the Ministry of New and Renewable Energy, which sanctioned five pilot projects with a total financial outlay of around ₹208 crore.[69] These projects involve 37 vehicles (buses and trucks) and 9 hydrogen refuelling stations, operating on 10 different routes across the country. Major domestic players, including Tata Motors, NTPC, ANERT, Ashok Leyland, HPCL, BPCL, and IOCL, and Reliance Industries, are actively involved in developing and testing both hydrogen fuel cell and hydrogen internal combustion engine (ICE) vehicles to support this transition.

This initiative is particularly focused on long-haul transport, where the high energy density and quick refuelling capabilities of hydrogen offer a viable alternative to conventional fuels. A significant early initiative was undertaken in 2021 by NTPC in Leh, marking India's first commercial deployment of hydrogen fuel cell buses at the world's highest altitude.[70,71] In June 2025, five such buses (integrated with pressure hydrogen dispensation system, 350 bar) were handed over to the Leh Administration for operations.[72] This project is supported by the world's first hydrogen fueling station, which is co-located with a dedicated 1.7 MW solar plant to provide clean power for its operations. This high-pressure hydrogen dispensation system is designed to operate in extreme, sub-zero temperatures, mitigating approximately 350 metric tons of carbon emissions and contributing 230 metric tons of pure oxygen to the atmosphere annually. The expansion of hydrogen mobility initiatives accelerated across multiple states through strategic partnerships and government support. In December 2024, NTPC signed a tripartite MoU with GRIDCO and CRUT for the green hydrogen mobility scheme in Odisha, planning to setup a green hydrogen fuelling station in Bhubaneswar along with hydrogen buses for short-haul and long-haul operation.[73] Similarly, in January 2025, NTPC REL signed MoU with Deendayal Port Authority for developing green hydrogen mobility project in Kandla Port, planning to setup hydrogen fuelling stations along with 11 hydrogen buses for short-haul operation.[74] Infrastructure development for urban mobility is also advancing, with Jakson Green Infinity shipping its first batch of 3.8 MW electrolysers in November 2024 for an inaugural green hydrogen refuelling station in the National Capital Region (NCR).[75] The momentum continued with BPCL partnering with KPIT Technologies in March 2025 to enhance hydrogen-based mobility in Kerala, involving the establishment of Hydrogen Refuelling Stations in Kochi and Trivandrum to support pilot mobility projects between the two cities.[76] Expanding the application of hydrogen, the Adani Group deployed India's first hydrogen fuel cell truck for mining logistics in Chhattisgarh in May 2025.[77] Each truck is equipped with three hydrogen tanks, allowing it to carry up to 40 tons of cargo with a range of 200km on a single fill. Toyota Kirloskar Motor Pvt Ltd (TKM) is also contributing it potential in this mission. Started with a pilot project together with International Center for Automotive Technology (ICAT), showcased (in 2022) the world's most advanced Fuel Cell Electric Vehicle Toyota Mirai which runs on hydrogen, TKM started supplying fuel-cell module to Ashok Leyland to build Fuel Cell Commercial Vehicle (2022-2023), and then collaborated with Ohmium® (in 2025) to expand its efforts in India and to explore across mobility sector and beyond.[78,79,80]

Indian Railways is a key participant in the green hydrogen transition, with plans to run 35 hydrogen trains under the "Hydrogen for Heritage" initiative on various heritage and hill routes.[81] This project is estimated to cost ₹80 crore per train, with an additional ground infrastructure cost of ₹70 crore per route. A pilot project (₹111.83 crore) to retrofit a Diesel Electric Multiple Unit (DEMU) rake with a hydrogen fuel cell is set to run on the Jind-Sonipat section of the Northern Railway.[82]

The maritime sector is also advancing hydrogen as a clean fuel through government initiatives and port-specific projects. The 'Panch Karma Sankalp' initiative, announced in May 2024, includes a provision for 30% financial support for green shipping and designates Deendayal Port and V.O. Chidambaranar Port as Green Hydrogen Hubs.[83] The Deendayal Port Authority (DPA) in Kandla has commissioned India's first megawatt-scale green hydrogen plant, a 1 MW facility developed by L&T under the "Make-in-India" initiative. This plant is expected to produce approximately 140 metric tonnes of green hydrogen annually.[84] Additionally, V.O. Chidambaranar Port has earmarked ₹41,860 crore to become a Green Hydrogen-Ammonia hub, allocating 501 acres of land to four firms for manufacturing and storage facilities.[85] Moreover, a budget of ₹115 crores has been earmarked under the National Green Hydrogen Mission for pilot projects in the shipping sector, focusing on retrofitting ships to run on green hydrogen or its derivatives, along with bunkering and refuelling facilities at key ports. These initiatives, to be implemented by 2025–26, will lay the groundwork for a green hydrogen ecosystem in shipping through technology testing, infrastructure development, and cost reduction over time.[86] The construction of India's first green hydrogen-powered ships, a joint effort by Cochin Shipyard and Mazagon Dock Shipbuilders, is underway, leveraging indigenous technology.[87]

While significant progress is being made, India's green hydrogen mobility sector faces considerable hurdles, including the high cost of green hydrogen production and the substantial investment required for nationwide infrastructure. Additionally, challenges such as the high cost of hydrogen storage tanks for H_2-ICE vehicles and the lack of a clear regulatory framework remain. Despite these issues, the ongoing pilot projects and strategic partnerships across the public and private sectors are crucial to paving the way for a more widespread adoption of hydrogen as a clean fuel in the future.

Power, Utility, and Miscellaneous

India's power and utilities sector is rapidly adopting green hydrogen to decarbonize electricity generation, gas distribution, and off-grid energy security solutions. Nonetheless, it has evolved beyond traditional industrial applications to encompass innovative research initiatives, specialized utilities, and cutting-edge technological demonstrations that collectively advance the nation's clean energy transition. The power and utilities sector adoption began with NTPC's groundbreaking initiative in April 2022, when the company partnered with Gujarat Gas Limited to implement India's first green hydrogen blending in a piped natural gas network at NTPC Kawas. The project utilized electricity from an existing 1 MW floating solar project to produce green hydrogen, which was initially blended with piped-natural-gas network (PNG) at 5% (would be scaled phase wise to reach 20%) concentration for cooking applications in NTPC Kawas Township, with plans for phased scaling to higher percentages.[88,89] This pioneering effort marked the first step toward decarbonizing the cooking sector and achieving energy self-sufficiency. Further, this work extends to hydrogen cooking demonstrations at its Greater Noida campus, where engineers designed specialized burners to address hydrogen's unique combustion characteristics including its almost invisible flame and 1200-1500°C temperature, producing only water vapor as emission.[90] The company also established India's first green hydrogen microgrid project at Simhadri featuring a 240kW solid oxide electrolyzer coupled with a 50kW solid oxide fuel cell for standalone operation, while developing direct seawater electrolysis pathways through collaborations with CSIR-CMERI and CSIR-NCL to address freshwater scarcity challenges associated with large-scale hydrogen production.[91,92] Gas utility integration expanded through GAIL's commissioning of a 10 MW PEM electrolyser at Vijaipur, Madhya Pradesh, in 2024.[93] The facility will produce 4.3 tonnes of hydrogen per day with 99.999% purity, initially for captive use and blending with natural gas for various processes. Adani New Industries Limited commissioned India's first off-grid 5 MW green hydrogen pilot plant in Kutch, Gujarat, powered entirely by solar energy and integrated with battery storage, featuring a fully automated closed-loop electrolyzer system designed for real-time responsiveness to renewable energy variability.[94] Meanwhile, SJVN Limited achieved a significant milestone in April 2024 with India's first multi-purpose green hydrogen pilot project at the 1,500 MW Nathpa Jhakri Hydro Power Station in Himachal Pradesh, where a 20 Nm^3/hr alkaline electrolyzer powered by a 1.31 MW solar plant produces 14 kg of green hydrogen daily for High Velocity Oxygen Fuel coating of turbine components and electricity generation through a 25kW fuel cell.[95]

The sector's technological advancement accelerated through specialized applications and innovative solutions addressing diverse energy needs across multiple domains. Defence applications reached new heights with NTPC's partnership (2024-2025) with the Indian Army for a solar-hydrogen microgrid at Chushul, Ladakh, will be providing 200kW of round-the-clock power at 4,400 meters altitude and -30°C temperatures, replacing diesel generators and avoiding 1,500 tonnes of CO_2 annually over a 25-year operational period.[96,97] Aviation sector integration commenced through BPCL's collaboration with Cochin International Airport Limited (CIAL) to establish India's first integrated green hydrogen plant and fueling station at Kochi Airport in 2024.[98] The 1,000kW project, targeting 2025 completion, utilizes cutting-edge technology to produce 100 Nm^3/hr of green hydrogen for airport vehicles, marking a significant step toward sustainable aviation ground operations. Space applications achieved historic recognition when ISRO successfully tested a 100W Polymer Electrolyte Membrane fuel cell aboard the PSLV-C58 mission, generating 180W power and serving as a precursor to future space station power systems.[99,100] These diverse initiatives collectively demonstrate India's comprehensive approach to green hydrogen development, spanning from fundamental research and novel production pathways to specialized applications across defense, space, and utility sectors, establishing the technological foundation necessary to support the nation's ambitious 5 million tonnes per annum green hydrogen production target by 2030.

Geographical Distribution of Projects

The state-wise analysis (Fig. 1) reveals a concentrated yet strategically distributed landscape of green hydrogen development across India, with Gujarat emerging as the clear leader in electrolyser capacity deployment at approximately ~7.4 GW (~21%, Fig. 1c) of electrolyser capacity across all development phases, followed closely by Andhra Pradesh (~6.5 GW) and significantly by Karnataka (~4.4 GW) and Odisha (~2.8 GW). Odisha dominates the national pipeline with around 2.4 million tonnes per annum (MTPA) of hydrogen production capacity (~20%, Fig. 1d) supported by largely the announced and planned projects for green ammonia and methanol by BPCL, Ocior, REFPL, Sembcorp, ReNew, and ACME. Landlocked states like Rajasthan with huge (Fig. 1b) renewable energy installed capacity have shown major allocation in the mission, specifically for utilization of green hydrogen in mainly green ammonia and fertilizer sector.

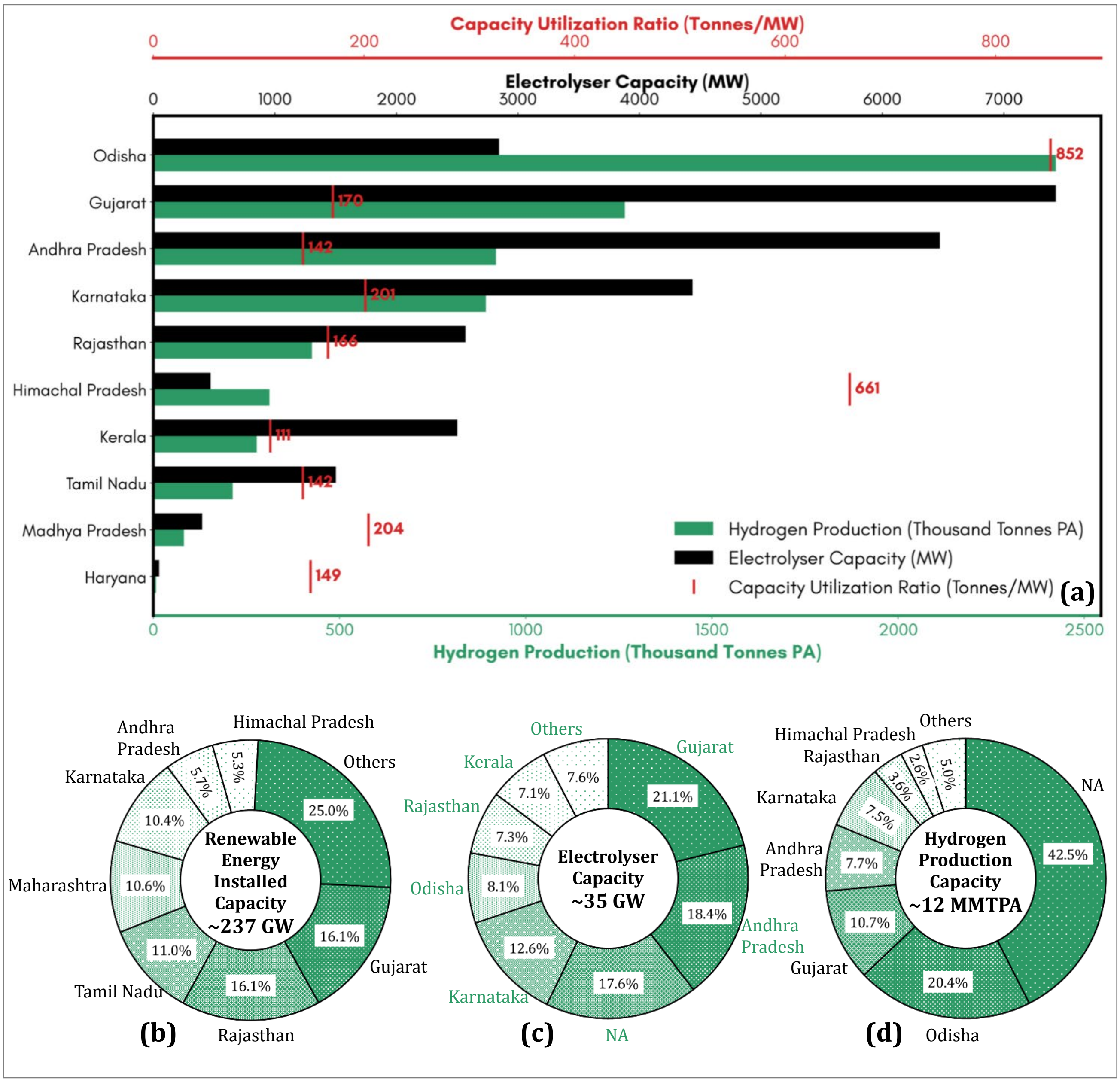


Figure 1. State-Wise (a) green hydrogen production capacity, electrolyser capacity, and capacity utilization ratio, percentage share of (b) installed renewable energy (RE) capacity, (c) electrolyser capacity, and (d) hydrogen project/production capacity (accessed, 24-08-2025).[101,102]

This distribution reflects a deliberate national approach to clean energy transition, with clear leaders emerging in both production capacity and electrolyser deployment; thus, the development concentrated in states that possess optimal combinations of renewable energy potential, industrial infrastructure, coastal strength, and export capabilities for both domestic energy security and global export leadership.

An electrolysis system with no inefficiencies, theoretically would require 39.4 kWh of electricity to produce a kilogram of hydrogen.[103] On considering current best processes for water electrolysis have an effective electrical efficiency of 70-80%, so that producing 1 kg of hydrogen (specific energy of 143 MJ/kg or about 40 kWh/kg) requires 50–55 kWh of electricity (PEM or alkaline electrolyzers).[103,104,105] However, older systems and larger-scale plants may have higher consumptions within the 60-100 kWh/kg range.[106] So, if the energy consumption is 50 kWh/kg for a continuous, year-round operation (8,760 hours), electrolyser with 1MW capacity may possibly produce around 175 TPA (ton per annum) of hydrogen, while it will be around 159 TPA in case of 55 kWh/kg consumption. On considering these two values as benchmark (159 TPA/MW and 175 TPA), "capacity utilization ratio (tonnes/MW)" metric is introduced in the Fig. 1 (red verticals dashes/lines) to bridge the gap between electrolyser capacity and annual hydrogen production. Even though this term is not standard, it captures the planned tonnes of hydrogen produced per megawatt of electrolyser capacity each year and reveals any mismatch in the parallel progress of electrolyzer and hydrogen projects. For example, the project capacity (across all phases of development) of the Odisha of 2,424,000 TPA of hydrogen production with 2,845 MW of electrolyser capacity indicates a capacity utilization ratio of 852 TPA/MW, which is 4.9 to 5.4 times of the benchmark of 159 TPA/MW (@50 kWh/kg) and 175 TPA (@55 kWh/kg). It also indicates that, for the hydrogen project capacity of 2,424,000 TPA of hydrogen production in Odisha would require around 13,851 MW to 15,245 MW of electrolyser capacity (for a continuous, year-round operation), which is currently 2,845 MW around one fifth of the required capacity. Similarly, In Himachal Pradesh, required electrolyser capacity would around 4 times of the current capacity. In case of the Gujrat, the capacity utilization ratio is around 170 (Fig. 1a), which is near to the benchmark of 159-175 TPA/MW, reflects that the allocated (across all phases of development) electrolyser capacity of 7,428 MW is less or more same of the required (7,235 MW – 7,963 MW).

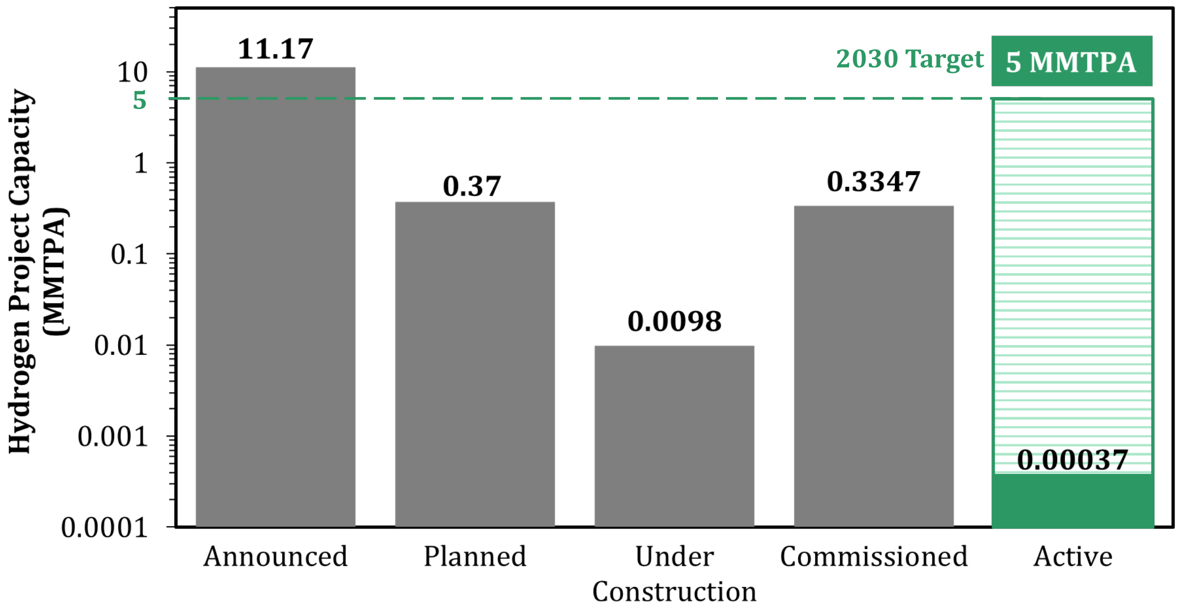


Figure 2. India's green hydrogen project pipeline (production capacity, MMTPA) by project status relative to 2030 target (accessed, 24-08-2025).[101]

Apart from the geographical distribution of projects, Fig. 2 depicts the hydrogen production capacity across the different development and deployment stages yet to take off and reach the 2030 target of 5MMTPA of active hydrogen production capacity. The hydrogen production and electrolyser capacity (current and required) for each development phase along with the calculated capacity utilization ratio, and required electrolyser capacity multiplier against the current capacity are tabulated in Table 1. Less or more, a balanced (as multipliers are near unity, in table 1) attention has been given parallelly for development and deployment of both the targeted hydrogen production and corresponding electrolyser capacities for active, planned, and under construction projects. However, around 125-times of the current electrolyser capacity would be needed to be commissioned to meet the commissioned hydrogen production capacity for parallel progress.

India's ambitious targets of 60–100 GW (potentially exceeding 200 GW) of electrolyser capacity by 2030 provide substantial buffer for renewable energy intermittency. The 5 MMTPA hydrogen mission with 60–100 GW electrolyser capacity yields multipliers of 0.3–0.53, meaning that even with one-third daily utilization (8 hours of renewable energy supply or electrolysis) or less efficient electrolysis than the assumed (70-80%), the targeted electrolyser capacity would sufficiently accommodate renewable intermittency and inefficiency while meeting production goals.

Table 1. Green hydrogen project analysis (accessed, 24-08-2025): capacity utilization ratios and electrolyser requirements by development status.[101]

Status	Hydrogen Production Capacity (TPA)	Electrolyser Capacity (MW)	Capacity Utilization Ratio (TPA/MW)	Electrolyser Capacity Required	Electrolyser Capacity Multiplier
Active	**370**	**2.4**	**154**	**2.11 – 2.33**	**0.88 - 0.97**
Announced	11172698.1	32585.37	343	63844 - 70268	1.96 - 2.16
Commissioned	334709.98	15.91	21043	1913 - 2105	120.5 - 132.35
Planned	374164.77	2301.05	163	2138 - 2353	0.93 - 1.02
Under Construction	9769.5	67.35	145	56 – 61.4	0.83 - 0.91
Grand Total	**11891712.31**	**35121.07**	**339**	67953 - 74791	**1.93 - 2.13**
2030 Target	*5000000*	*60000-100000*	*83 - 50*	*28571 - 31446*	*0.3 – 0.53*

The success of transforming these announced capacities into operational infrastructure will determine whether India achieves its dual objectives of domestic industrial decarbonization and emergence as a global green hydrogen export powerhouse. Only 0.007% of the target (5MMTPA) green hydrogen project is active, while nearly 7% of the 2030 target are either commissioned or under-construction till September 2025. There are huge opportunities in different sectors of green hydrogen economy along with numerous technical, financial, operational, and other challenges which need urgent attention to meet the overall target in the next 5 years.

1

MARKET TRANSPARENCY & INFORMATION INFRASTRUCTURE

This Section addresses the crucial need for clear market visibility. Without robust systems for real-time data on demand, supply, and pricing, stakeholders can face uncertainty, hindering confident investment and efficient project deployment. The insights explore how an effective market intelligence infrastructure, including data collection and exchange mechanisms, can foster transparency and informed decision-making for India's green hydrogen ecosystem, building upon existing initiatives like the Green Hydrogen Certification Scheme of India.

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India's ambition to produce 5 MMT of green hydrogen annually by 2030 and eventually 10 MMT including exports reflects both a domestic decarbonisation imperative and a strategic opportunity to establish India as a reliable supplier to the European Union, Germany, Denmark, Japan, South Korea and other importers.[107,108,109] Launched in January 2023, the National Green Hydrogen Mission and its Strategic Interventions for Green Hydrogen Transition (SIGHT) scheme offer subsidies for electrolyser manufacturing and production (peaking at USD 0.66/kg and tapering to USD 0.40/kg over three years), yet grey hydrogen still dominates India's hydrogen economy and cannot overcome the green–grey cost gap, USD 3.5–5/kg versus USD 1.5–1.8/kg, above breakeven thresholds for many sectors.[110] Developers face high capital costs for bespoke logistics chains, and financing green hydrogen projects remains difficult without concessional capital, guarantees and blended-finance instruments to lower India's 9–11 percent WACC, which far exceeds that of advanced economies.[111,112,113]

As green hydrogen continues to establish its role within the evolving energy landscape and emerging as a vital decarbonisation tool for hard-to-abate sectors like refining, fertilisers, steel, cement, and heavy transport, India must address not only the challenge of cost competitiveness but also the critical need for a comprehensive hydrogen distribution and storage infrastructure; moreover, the development of medium-term demand sectors such as steel, mobility, and city-gas distribution will necessitate substantial new infrastructure investment, thereby introducing additional layers of uncertainty in project planning and deployment. Furthermore, fragmented or outdated data on demand centres, project pipelines, renewable energy tie-ups, and policy incentives obscures true market dynamics. For instance, while projections suggest only ~2 MTPA of domestic demand by 2030, supply ambitions are more than double. The imbalance underscores the importance of transparent data to track domestic substitution pathways while aligning export-focused capacity to ports like Kakinada, Odisha, and Gujarat.[114]

To address these barriers, India must invest in an integrated market-intelligence and trading ecosystem. First, a robust Market Intelligence Infrastructure must deliver granular, near–real-time visibility into demand by sector (refining, fertilisers, steel, mobility, city-gas, export derivatives) and geography (core clusters in Gujarat, Maharashtra, Uttar Pradesh; emerging hubs in Jharkhand, Chhattisgarh, Odisha, Karnataka), as well as supply details; announced, under-construction and commissioned projects with electrolyser specifications, operational utilisation, outages and renewable energy feedstock availability. Second, a dedicated Green Hydrogen Exchange (GHX-India) should institutionalise transparent price discovery through standardised product definitions, contract tenures (spot, short-term, long-term), delivery hubs, real-time bid/offer matching, benchmark price indices and embedded carbon premiums, supported by an independent clearing house and risk-management instruments such as futures and contracts-for-difference. Third, a Centralized Market Intelligence Unit (CMIU) under MNRE must ensure data integrity through uniform reporting protocols, independent verification and secure, role-based data governance; conduct forward-looking market analysis and cost-curve modelling; and disseminate insights via public dashboards, open APIs and targeted bulletins to policymakers, investors, developers and off-takers.

This section explores three interrelated questions that underpin this vision: how to construct granular demand and supply measurement systems that de-risk investment and inform optimal siting; how to design GHX-India for credible, continuous price discovery and liquidity; and how to empower CMIU with the functions, governance and strategic enablers necessary to transform fragmented data into actionable intelligence. Together, these mechanisms will foster transparency, reduce market uncertainty, align capacity build-out with actual demand, and ultimately accelerate India's transition to a competitive, scalable and globally integrated green hydrogen economy.

Granular Demand & Supply

Achieving India's ambitious 5 MMT green hydrogen target by 2030 requires a robust, transparent market intelligence system. To address the current opacity, stakeholders can collectively develop a national data framework, the India Green Hydrogen Market Observatory (IGHMO). This system would provide granular, real-time data to de-risk investments and optimize project deployment across the value chain.

What the System Must Measure and Why

Demand (granular, near-real-time)

The IGHMO would capture demand dynamics across three critical vectors:

- ***By sector & application:*** Focus initially on refineries, fertilizers, and petrochemicals as anchor loads, then expand to steel, mobility, city-gas, and export derivatives like green ammonia (NH_3) and methanol (MeOH). The system would also track the co-firing of hydrogen in gas turbines, for which successful trials have been conducted and need to be commercialized.
- ***By geography/cluster:*** The system would prioritize existing hydrogen consumption hubs in Gujarat, Maharashtra, Uttar Pradesh, Rajasthan, and Madhya Pradesh before expanding to emerging steel-producing states like Jharkhand, Chhattisgarh, Odisha, and Karnataka.
- ***Export-linked demand:*** Given that domestic demand may only reach ~2 MTPA by FY 2030, exports are critical to utilize the 5 MTPA supply ambition, so the system must track export offtake intent and port readiness.

Supply (bankability-grade visibility)

The IGHMO must provide bankability-grade visibility, including:

- ***Project registry & status:*** A comprehensive registry would track announced, under-construction, and commissioned projects with details on electrolyzer specifications, hydrogen capacity, end-use, and precise location. This serves as the baseline data for a national-scale schema, with details publicly available on platforms like the National Green Hydrogen Mission (NGHM) website.
- ***Operational capacity & utilization:*** The system would provide hourly/daily production data, including outages and curtailments, to show real availability beyond nameplate capacity.
- ***Feedstock & inputs:*** The system would track dedicated renewable energy (RE) capacity, grid/open-access arrangements, and water/land availability, which is crucial as studies suggest approximately 125 GW of additional RE capacity is needed to meet the hydrogen target.

Enablers & Risks (location/geographical decisions)

The system would also track key enablers and risks related to project location decisions:

- ***Infrastructure readiness:*** Hub development near demand centres and ports, including storage, trucking, pipelines, and power evacuation.
- ***Policy & incentives:*** NGHM, Strategic Interventions for Green Hydrogen Transition (SIGHT) components, and state policies would be captured as machine-readable metadata for project filters and financial models.
- ***Financeability indicators:*** The presence of standardized offtake terms, risk-mitigation options (e.g., grid-sale fallback), and blended finance instruments would be tracked to address investor uncertainty.

The Operating Model: IGHMO

Governance & Roles: The IGHMO would be managed by the Ministry of New and Renewable Energy (MNRE)/NGHM as the central custodian, with the Solar Energy Corporation of India (SECI) as the operating agency for data collection and state energy departments as regional data stewards.

- ***Nodal custodian:*** MNRE/ NGHM Programme Steering with a dedicated data unit; SECI as operating agency for data collection & publication; state energy departments as data stewards for clusters. Further, the India Energy Security Scenarios (IESS) 2047 v3.0, a scenario-based accounting tool developed by NITI Aayog in collaboration with IIT Bombay, enables policymakers, researchers, and industry stakeholders to simulate and assess long-term energy pathways across demand and supply sectors till 2047, and does provide for the integration of recent policies such as the Green Hydrogen Mission.
- ***Mandatory reporting via incentives:*** Tie SIGHT/ other benefits, open-access approvals, and hub support to data sharing (project and operational). Regular studies need to be undertaken by nodal custodian and other regulatory authorities to assess and underscore the incentives and hub development as central policy tools - and use them as data levers.
- ***Industry participation:*** Refineries, Fertilizer Plants, Steel Plants, City Gas Distributions (CGDs), Ports, EPCs, Electrolyser OEMs and Project Developers provide structured feedback for the improvements in the governance structure as per the evolving needs. Finance institutions contribute anonymised term-sheet markers (tenure, price bands, risk mitigants) consistent with the industry's requirement for the standardization.

Data Architecture (standards-first): The system would utilize standardized data schemas for project metadata, demand point characteristics, and operational telemetry. This includes details such as Project ID, location, electrolyzer technology, RE PPA details, end-use, and commissioning timelines.

- ***Canonical project schema (minimum fields):*** Project ID, promoter(s), location (latitude/longitude & cluster), electrolyser tech/capex, RE PPA details, water source, product (H_2/NH_3/MeOH), offtake type & tenure, commissioning timeline, status, and verified capacity. Such details provide for the details of the projects in this segment and adds to the bankability of the same.
- ***Demand point schema:*** Facility ID, sector, current grey-H_2 consumption, substitution pathway, mandated/voluntary offtake, switching curve (cost vs. carbon), and infrastructure dependencies, aligned with the demand-site map.

- ***Operational telemetry:*** Hourly production, utilisation, outages, RE availability, grid-draw (kWh/kg), water draw, storage inventory, dispatches by destination (domestic cluster vs. port).
- ***Policy metadata registry:*** Versioned NGHM/ SIGHT/ state-policy attributes (eligibility, fiscal support, charge waivers, banking rules), enabling filterable "where to build" analytics.
- ***Hub infrastructure layers:*** Port capacity, evacuation assets, storage/logistics costs; NGHM's intent to set up hydrogen hubs should seed the first two "data-rich" hubs as pilots.

Data Collection & Assurance: Data acquisition would leverage regulatory feeds, enterprise APIs, and utility system interfaces. Independent verification mechanisms, including monthly reconciliation and comprehensive audit trails, would ensure data accuracy. Confidentiality would be maintained through a sectoral data trust with role-based access.

- ***Pipelines:***
  - **Regulatory feeds:** SECI tenders/SIGHT awards and state single-window portals.
  - **Enterprise APIs:** Secure push from plants/OEMs.
  - **Utility/system feeds:** Open-access schedules, ISTS/SLDC wheeling, curtailment logs for RE linked to H_2 projects (to evidence bankability).
- ***Verification:*** Independent data verifiers attached to each hub; monthly reconciliations between reported nameplate vs. metered output; audit trails.
- ***Confidentiality:*** A sectoral data trust with role-based access; public dashboards show aggregated cluster stats; lenders/off-takers access asset-level views via Non-Disclosure Agreements (NDAs) and consent.

The Product: Dashboards, APIs, and Decision Tools

Public Dashboards (cluster-level, updated daily/weekly): Publicly available dashboards would display cluster-level demand and supply dynamics.

- ***Demand now/next:*** Grey → Green switch potential by sector & cluster; pipeline of mandates and corporate commitments.
- ***Supply funnel:*** Announced → financed → under-construction → commissioned, with expected commissioning dates and risk flags (RE tie-up, water permits, land).
- ***Hub scorecards:*** Infrastructure readiness (storage, port, evacuation), policy support, and average delivered cost curves per hub (the usefulness of cost-curve framing is to be explored further).
- ***Finance tracker:*** The system would track indicators such as the share of projects with standardized offtake and verified grid-fallback options, which are crucial for due diligence and attracting investment.

Pro Tools (for investors, lenders, developers): Specialized analytical tools would include a location optimizer, an offtake contract analyzer, and an export readiness view. The location optimizer would help minimize mis-siting risks by overlaying data on demand, RE resources, and infrastructure.

- ***Location optimizer:*** Overlay demand sites, RE resources, transmission access, water, land, and state incentives to rank locations per tonne-delivered-H_2/ NH_3 LCOX. (Responds directly to the "sub-optimal location choice" risk.)
- ***Offtake analyzer:*** Benchmarks contract conditions, indexation formulas and volume flex (mid-term PPAs analogy) to speed diligence and term-sheet convergence. Adequate regulatory measures are required to be in place for addressing concerns in this regard.
- ***Export readiness view:*** Port-adjacent projects, derivative conversion capacity, and signed MoUs for exports, starting with exemplar platforms like Kakinada. Further, the uncertainties of trade relations with countries/ nation-blocs must be tackled for smooth business transactions over long-term. The policy makers have to be proactive in navigating the troubled waters (wherever required) as we are witnessing in the second presidency of US President Trump's reign since January 2025.

Make Data Mandatory - Tie it to Value Creation and Permits

Incentive-linked reporting: Access to SIGHT subsidies, inter-state transmission system (ISTS) waivers, and hub capex support would be contingent on timely data submission and MRV (Measurement, Reporting, and Verification) compliance.

Standardized Offtake Templates: The system would promote standardized contracts with machine-readable schedules and pricing to facilitate comparisons for lenders. There has to be standard guidelines such as 10-year or 15-year for committed offtake, embed digital, machine-readable schedules/pricing clauses so lenders can compare apples-to-apples.[114]

Fall-back/Real-options disclosure: The system would mark projects that have the ability to sell power to the grid when offtake agreements stall, providing a concrete, finance-relevant field for investors.

Start with Two Pilot Hubs, Then Scale

Pilot Selection: The implementation would begin with a phased approach in two data-rich pilot hubs for a 12-month duration. The proposed pilots are the Western corridor (Gujarat-Maharashtra)- high current hydrogen use, port access, early OEM/manufacturing presence and the East-coast export hub (Andhra Pradesh/Odisha)- port-centric green ammonia platforms (e.g., Kakinada), strong export thesis.

Deliverables: Live project registry; Periodic (fortnightly/monthly) demand substitution tracker for refineries/fertilisers; hub infrastructure scorecard; lender's bankability dashboard, public API etc.

Scale-out: After stabilizing operational protocols, the system would be expanded nationally to include steel-producing belts (Jharkhand/Chhattisgarh/Odisha/Karnataka) and northern clusters (UP/Haryana) once telemetry and policy metadata pipelines stabilize.

KPIs for Transparency for Every Stakeholder

Coverage: The system would aim for ≥90% project coverage for commissioned and under-construction projects reporting operational (ops) telemetry; ≥80% of grey-H_2 consumers mapped with substitution roadmaps.

Latency: Data latency standards would be set at ≤7 days, with daily updates for operational telemetry where feasible (weekly acceptable in initial phase).

Financeability: KPIs would include the share of projects with standardized offtake and verified grid-fallback, as well as the number of projects using guarantees/Viability Gap Funding (VGF).

Hub Readiness: The system would measure quantifiable reductions in project location-selection risks and improved time-to-financial-close for projects within the hubs.

Why this will Reduce Investor Uncertainty

The IGHMO would reduce investor uncertainty by:

- ***Location clarity:*** Combining demand-site maps with infrastructure and policy layers to minimize mis-siting risk.
- ***Bankable data:*** Encoding financing insights, such as standardized offtake and real-options, to improve project bankability.
- ***Policy-aligned growth:*** Ensuring analytics align with NGHM/SIGHT milestones and state policies, guaranteeing that incentives are captured accurately.
- ***Export utilization:*** Tracking export-oriented capacity to bridge the gap between domestic demand and the 5 MTPA supply ambition.

By building a national IGHMO with clear governance and mandatory, incentive-linked reporting, India can address the current lack of precise, accessible data. This system would standardize project, demand, and financeability signals, improving project-siting decisions and accelerating efficient capital deployment across India's green hydrogen value chain.

Facilitating Transparent Price Discovery

Recent price discovery milestones, IOCL's ₹397.33/kg green hydrogen auction (27% lower than the global average cost of producing green hydrogen) and SECI's green ammonia tariffs as low as ₹49.75/kg, demonstrate the power of competitive, market-driven mechanisms.[115,116] A dedicated exchange could amplify these gains by fostering liquidity and anchoring investor confidence. While the market is emerging, a central exchange hasn't been fully established, even as the National Green Hydrogen Mission focuses on creating demand, reducing costs, and attracting investment to build the ecosystem necessary for such a platform. An independent Green Hydrogen Exchange (GHX-India) is quite essential and this section examines how GHX-India should be structured to facilitate transparent price discovery, enhance market liquidity, and strengthen investor confidence amid India's rapidly expanding hydrogen economy.

Core features of the Green Hydrogen Exchange

Standardisation for comparability & liquidity

- ***Product definitions:*** Align with the Green Hydrogen Certification Scheme of India (GHCI) for "green" eligibility (RE sourcing, water criteria, emissions accounting). Extend to derivatives (NH_3/MeOH) with transparent conversion factors.
- ***Contract types:***
  - **Spot (day-ahead, intra-day):** For flexibility and balancing needs.
  - **Short-term (1–3 years):** Mirrors mid-term PPAs, giving off-takers optionality while reducing bankability gaps.

  - **Long-term (10–20 years):** Suited for anchor investments (refineries, fertilisers, steel).
- ***Standardised delivery units:*** For example, Kg for gaseous H_2, Tonne for NH_3/MeOH, linked to trading hubs (cluster or port).

Transparent price discovery

- ***Real-time bid/offer book:*** Live matching engine showing cleared price and depth of market, differentiated by product form and hub location.
- ***Price indices:*** Benchmark indices by cluster (e.g., Gujarat, Odisha/AP, UP belt), by product (gaseous H_2, NH_3, MeOH), and by tenure (spot/short/long).
- ***Carbon premium disclosure:*** Prices must explicitly show avoided CO_2 cost or GHCI-certified premium vs. grey hydrogen baseline.

Integrated certification & traceability

- ***GHCI integration:*** Automatic linkage of certificates to traded lots, with attributes (RE source, grid draw, emissions profile, water use).
- ***Smart registry:*** Online and secure ledger for certificates, ensuring no double counting and full provenance for export compliance.

Operational mechanisms for efficiency and trust

Clearing & settlement

- ***Independent clearing house:*** Guarantees payment and delivery, reducing counterparty risk.
- ***Physical vs. financial settlement:*** Allow physical delivery (linked to hub storage/port tanks) and financial contracts (cash-settled indices).

Delivery points & hubs

- ***Cluster-based delivery obligations:*** Focus on refinery/fertiliser clusters (UP, Gujarat, Maharashtra) and export hubs (AP/Odisha, ports).
- ***Hub infrastructure visibility:*** Link the exchange to hub scorecards (storage, port readiness, RE tie-ups).

Risk management instruments

- ***Forward/futures contracts:*** Hedge price volatility for steel and fertiliser off-takers.
- ***Contracts-for-difference (CfDs):*** Indexed to grey H_2 or natural gas prices, stabilising supplier revenues.
- ***Guarantees & insurance products:*** Blended-finance institutions backstop credit risk for new entrants.

Governance & participation

- ***Independent regulator:*** Exchange licensed by CERC or a new clean-energy market regulator.
- ***Mandatory disclosure for exchange participation:*** Project developers accessing SIGHT/NGHM support list tradable capacity and forward offers.

- ***Inclusivity & coverage:*** Enable participation by refineries, fertiliser plants, steel producers, CGD companies, ports, export aggregators, and global buyers.

Value to market participants

- ***For investors/lenders:*** Transparent benchmarks reduce uncertainty and enable long-term financial models.
- ***For developers:*** Exchange offers route-to-market beyond bilateral PPAs.
- ***For policy makers:*** Data from the exchange feeds into the proposed Green Hydrogen Market Observatory.

Implementation pathway

- ***Pilot (2025–26):*** Start with bilateral-trade clearing (ammonia cargoes at east-coast ports; gaseous H_2 in refinery hubs).
- ***Scale-up (2027–28):*** Add spot trading, rolling indices, short-term contracts.
- ***Mature phase (2029–30):*** Full suite of spot, forward, futures, and CfDs, integrated with GHCI and cross-border certification schemes.

An independent Green Hydrogen Exchange, anchored on standardisation (GHCI), transparent price indices, cluster-linked delivery hubs, risk-hedging instruments, and strong clearing mechanisms, will unlock liquidity, de-risk investments, and anchor India's ambition of 5 MMT green hydrogen by 2030.

Enhancing Market Intelligence Governance

To accelerate India's journey toward its 5 MMT green hydrogen target by 2030, a Centralized Market Intelligence Unit (CMIU) must serve as an agile, independent hub for reliable, near–real-time insights across the hydrogen value chain.

Core Functions of CMIU

Data Integrity & Standardization

- Define uniform reporting protocols for project developers, electrolyser OEMs, refineries, fertiliser plants, and steelmakers.
- Verify and audit key metrics, capacity, production, RE tie-ups, water sourcing, offtake contracts, emissions intensity, to ensure accuracy and comparability.
- Integrate with the Green Hydrogen Certification Scheme to validate "green" credentials.

Market Analysis & Forecasting

- Perform sector-wise demand modelling (refining, fertilisers, steel, mobility, exports) mapped to geographic clusters.
- Maintain a dynamic project pipeline tracker, announced, financed, under construction, commissioned, with risk flags on RE supply, land permits, and policy changes.
- Develop cost-curve and competitiveness indices for hydrogen forms (gaseous, ammonia, methanol), incorporating location-specific RE tariffs and infrastructure costs.

Information Dissemination & Transparency

- Publish cluster-level dashboards and bulletins on demand substitution potential (grey → green), supply pipeline and operational status, and price benchmarks and financing trends.
- Provide open APIs for investors, developers, and policymakers to access aggregated data feeds.
- Act as a neutral data hub feeding into exchanges and policy instruments, reducing information asymmetry.

Strategic Enablers for Effective Governance

- ***Policy linkage:*** Make or link data submission to the CMIU a condition to access NGHM/ SIGHT incentives, RE open-access waivers, or hub support.
- ***Collaboration with states:*** Partner with state energy departments and industry clusters for granular, localised reporting.
- ***Integration with financial institutions:*** Incorporate anonymized financing terms on tenure, pricing, and risk mitigants from lenders to benchmark bankability.
- ***Global interoperability:*** Align data standards with key markets (EU, Japan, Korea, and other countries) import requirements to support India's export ambitions.

Impact on the Hydrogen Ecosystem

- ***For Investors/ Lenders:*** Investors and Lenders gain confidence from standardized metrics, greater certainty on project viability and demand signals.
- ***For Developers:*** Visibility into optimal siting, competitive benchmarks, and financing terms.
- ***For Policymakers:*** Evidence-based calibration of incentives and hub development based on credible, granular data.
- ***For Off-takers (Buyers/Consumers):*** Transparent demand/ supply data to negotiate standardised contracts.

By embedding rigorous verification, predictive analysis, and transparent dissemination, the CMIU will transform fragmented data into actionable intelligence, de-risking investments and guiding India's green hydrogen transition. In sum, India's green hydrogen sector stands at a pivotal juncture. On one hand, strong policy intent, early industrial pilots, and global demand signals provide momentum. On the other, cost competitiveness, infrastructure bottlenecks, and financing constraints risk slowing progress. By institutionalising high-quality market intelligence through a centralised unit, India can mitigate uncertainty, align capital deployment with real demand, and ensure that the NGHM's ambitions are not undermined by fragmented data flows. This discussion sets the stage for exploring how such a unit could function and the value it would deliver to the ecosystem.

2

INCLUSIVE MARKET DEVELOPMENT & INNOVATIVE BUSINESS MODELS

Ensuring broad participation in the green hydrogen economy is vital for equitable growth across India. This section delves into innovative business models and strategies that can empower smaller players like MSMEs, facilitate fair access to essential technologies such as electrolyzers, and foster localized demand aggregation. By exploring these approaches, we aim to democratize market access and accelerate widespread, inclusive adoption of green hydrogen.

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India has recognized green hydrogen as one of the means for clean energy transition. Government of India has launched National Green Hydrogen Mission in 2023 to produce 5 million tonnes per annum (MTPA) of green hydrogen by 2030 as a 1st step in the journey towards hydrogen economy. The government has also introduced a Green Hydrogen Purchase Obligation scheme requiring initial 10% substitution of grey hydrogen with green hydrogen by refineries and fertilizer producers and gradually scaling up to 25% substitution in subsequent years.

Several organisations have initiated pilot projects/ investments in green hydrogen, and multiple states are formulating policies to attract investments. State-run oil refiners have planned investments worth ₹2 Trillion.[2] While tenders to produce 42,000 tonnes/ year of green hydrogen have been already issued, 128 more will be issued based on the outcome of these tenders. However, future evolution of Green Hydrogen will depend on factors such as technology development and level and pace of deployment.

India's hydrogen demand is expected to reach 12 MTPA by 2030 from current consumption on 5-7 MTPA. In India, nearly all hydrogen is currently produced as grey hydrogen via Steam Methane Reforming (SMR) and every tonne of this hydrogen emits ~10 tonnes of CO_2.[21] Decarbonizing hydrogen production is crucial for achieving net-zero targets in industry, transport, and energy. This is where green hydrogen comes into picture, "A clean, sustainable alternative produced using renewable energy sources."

Green Hydrogen can be utilised for blending with Natural Gas in CGD and CNG networks and heating applications in various industries. Adani Total Gas ltd. has started blending 2.2–2.3% green hydrogen into PNG network in Ahmedabad and GAIL and NTPC are working on similar initiatives. At present Green Hydrogen is facing challenges like high production costs ($ 4-6 per kg), limited electrolyzer manufacturing capacity, lack of storage and transportation infrastructure, safety concerns and insufficient demand aggregation. In comparison to Green Hydrogen costing, blue hydrogen and grey hydrogen are much more cost competitive with $ 1.5-3 per kg, which makes offtake of green hydrogen dependent on incentives and supportive policies.

Storage and transportation challenges can be minimised by localising Hydrogen production with continuous offtake which is only possible through inclusive market development and equitable access of Green Hydrogen to local consumers. Development of an inclusive market requires integrating small and medium enterprises (SMEs), startups, state backed financial support to lay foundation for a resilient green hydrogen value chain. Localized pilot projects demonstrating hydrogen usage, hydrogen offtake as per demand and demand-side incentives for end-users to switch from conventional fuels to hydrogen will help drive adoption beyond large consumers.

Furthermore, localised production models tailored to the region-specific energy requirements of industrial clusters and remote areas will enhance access to hydrogen-based energy. This approach will not only address local demand effectively but also contribute to energy self-reliance and resilience. Creating standardized frameworks for safety, certification, and pricing will help in building market confidence.

India is making significant efforts in initiating its green hydrogen journey, like government has planned to deploy around 1,000 hydrogen powered trucks and buses by 2030.[2] However, unlocking its full potential requires a comprehensive and inclusive approach including policy alignment, stakeholder collaboration, capacity building, and infrastructure support to ensure green hydrogen is adopted as an energy source across the country.

Decentralized Marketing & Branding

India's energy use is highly diverse, with coal supplying about 60% of power and industrial clusters consuming nearly 75% of total energy. This makes region-specific marketing essential to push for Green Hydrogen cause. Green Hydrogen adoption faces barriers like high storage/ transport costs and production 2X–3X costlier than grey hydrogen. India consumes **~900 MT of Coal annually**, so shifting from traditional fuels to hydrogen requires behaviour change and trust building.[117] Localized campaigns can effectively address safety concerns, highlight cost savings, and showcase live demonstrations, something national campaigns may struggle to do. Key elements for localized market development shall include-

- **Sector specific messaging** for consumers with different energy mixes. Decentralized marketing enables specific campaigns like H_2 based clean Steel, clean mobility, H_2 powered agricultural machinery and heating applications in industries. Such tailored messaging not only resonates with local needs but also aligns with broader policy targets. Likewise on lines of European Union aiming for green hydrogen to make up 42% of industrial hydrogen us by 2030.
- **Increasing Awareness and Trust:** MSMEs account for ~30% of India's GDP and ~11 Crore jobs, local entrepreneurs familiar with local context can build trust faster than top-down messaging.[118]
- **Leveraging local connections** to speed up outreach and distribution, especially in regions with limited infrastructure or low visibility of clean energy initiatives. Likewise, Airbnb model of leveraging hosts and guests as authentic brand ambassadors.
- Building an ecosystem **by empowering local businesses** to handle customer engagement and last-mile delivery in the green hydrogen value chain.

Ultimately highlighting local benefits is imperative to success of green hydrogen marketing campaign and development of local ecosystem for an inclusive and impactful growth.

Ensuring Equitable Access to Electrolyzers

Technology alone cannot beat Economic constraints. High capital cost of electrolyzers, ranging around **$2000–$2,450 per kW** for non-Chinese origin and **$750-1,300/kW** for Chinese origin is creating significant barriers for smaller players who often lack the scale, purchasing power, or financing options available to larger industry participants.[119]

Storage and transportation further add 30-50% to overall project cost depending on distance and mode (pipeline, compressed, or liquefied hydrogen). For wider adoption, small players need modular, affordable electrolyzers to produce required hydrogen on-demand at the point of consumption. This "Water-Tap" model promotes flexibility, efficiency, and decentralization in green hydrogen production.

However, policy intervention is necessary to avoid Electrolyzers supply getting concentrated in hands of few large players. Following initiatives can ensure equitable access to Electrolyzers -

- **Standardised Electrolyzer Modules** (**1-5 MW** for MSME's, mobility and small industries and 10-50 MW for industrial clusters, agriculture machinery, local utilities) are affordable, manageable and reduces inventory and dependence on specific suppliers.
- **Government-financed** or **state-owned electrolyzer facilities** can be made accessible to local developers without requiring full ownership. A **Build-Own-Operate** (BOO) model which is already proven in industrial gases supply can unlock the potential for hydrogen.
- **Aggregated Procurement Models** based on demand aggregation can bring down pricing by around 10-15% and secure better contractual terms.
- Incentivizing **local manufacturing** can cut costs by approx. 30-50% over time, enhance supply chain resilience and create local employment, drive self-reliance while targeting Green Hydrogen Cost at < $2/kg H_2 by 2030.
- **Innovative Financing Mechanisms** like Government backed loan guarantees, concessional finance and equipment leasing can substantially reduce upfront capital burdens for smaller entrants.

Democratizing accessibility of electrolyzers will not only increase participation but will ensure a competitive, diverse, and resilient green hydrogen market.

Optimizing Localized Demand Aggregation

Technology follows market demand. So, establishing a sustainable and consistent market demand base is essential to laying foundation for a robust Green Hydrogen Ecosystem.

Analysing the industrial clusters, community centres, and transportation infrastructure will help in understanding of the current energy mix and identify opportunities where green hydrogen can supplement existing fuel sources or progressively replace conventional fuels to cut emissions. For example, 1 kg of Green Hydrogen can replace 3.3 litres Diesel, thus avoiding **~8.8 kgs of CO_2** and ~55-60 Kg of Hydrogen is required to produce 1 Ton of Green Steel through DRI route.[120,121]

Engaging specific user groups will help in aggregating demand for Green Hydrogen. A digital marketplace can then aggregate multiple SME demands, let's say 20-50 SMEs into 100–500 kg/day clusters considering utilization of >70% facility load, for bulk procurement and shared logistics. Centralized production based on predictive analysis can serve local clusters anchored by couple of large consumers (making > 50% of demand and mitigating offtake risks). With pipeline transport costing around $ 0.30–0.40/kg, strategically located hubs will optimize green hydrogen price. For example, in UK Project Union aims to prepare a network of 1500 miles pipelines (across Great Britain) by repurposing existing pipelines and building new ones to transport 100% hydrogen, linking to various industrial clusters.

Local entrepreneurs leveraging the brand credibility of established Green Hydrogen producers shall operate hydrogen hubs offering subscription-based sales to users like farmers, vendors, and industries. MSMEs making up **90% of businesses worldwide** and providing **70% of jobs** (World Bank) can rapidly expand green hydrogen adoption at the grassroots.

Co-locating hydrogen facilities with renewables can cut costs by using solar power available at ₹3–3.5 /kWh, the threshold for competitiveness. This will boost grid stability, strengthen long-term financing, and will ultimately support India's 2030 target of 5 MT green hydrogen.

3

VALUE CHAIN OPTIMIZATION & COST REDUCTION

Achieving cost competitiveness is paramount for green hydrogen's widespread adoption in India. In this section, we examine critical aspects of value chain optimization, focusing on strategies to reduce transportation and distribution costs. We also explore the development and deployment of scalable, diverse storage solutions, which are essential for ensuring consistent supply and enhancing the economic viability of green hydrogen projects throughout the country.

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Achieving cost competitiveness is crucial for scaling green hydrogen across India's diverse sectors, including, industrial, mobility, and power. While the costs of electrolyzers and renewable power continue to fall, logistics, including storage, long-distance transport, and last-mile delivery, can account for a substantial portion of the final delivered hydrogen price, demanding equal attention. A crucial, yet complex, question for the green hydrogen sector is whether it is more economical to produce hydrogen near cheap renewable energy sources and transport it, to generate it closer to demand centres, or to find an optimal location somewhere in the middle. Answering this requires a careful cost-benefit analysis that considers the availability of renewable energy sources and the electricity prices at both the production and demand sites. Moreover, the design of the logistics chain critically depends on understanding how factors such as the transport route's length, the chosen mode of transportation, and storage methods collectively impact the overall cost, making these considerations paramount for achieving economical hydrogen.

Given the geographical disparity between renewable-rich states like Rajasthan, Gujarat, Tamil Nadu, Karnataka, and Maharashtra and the country's widespread demand, an optimized transportation strategy is essential. To encourage market development and identify sectors ready for scaled consumption, a focus on industries with high near-term demand potential is crucial. Refineries, ammonia/fertilizer plants, and steel/iron industry along with other mid-high energy intensive industries, in particular, are expected to be key demand centres by 2030, offering a foundation for creating a robust market. An optimized transportation strategy is crucial for a successful hydrogen economy. In many key industrial hubs, such as the refinery and fertilizer plants in Karnataka, chemical and fertilizer in Rajasthan, iron and steel clusters in Odisha, or the chemical, fertilizer, and export sectors in Maharashtra and Gujarat, local hydrogen generation using readily available solar resources could entirely bypass the need for long-distance transport. This localized approach is a highly effective way to minimize logistical costs and directly serve industrial demand clusters with green hydrogen.

The unique properties of hydrogen, such as its low density, flammability, and potential for leakage, boil-off, and material embrittlement, require specialized solutions.[122,123] For long-distance transport, pipelines offer the most economical solution but demand significant capital investment.[124] Until such networks are widespread, specialized trucks and tanker ships, which carry hydrogen in compressed, cryogenic, or chemically-bound forms like ammonia, will remain vital, despite their higher costs and energy penalties. Similarly, a portfolio of storage solutions is needed to ensure a stable supply, especially given the intermittent nature of renewable energy. High-pressure gas tanks are a proven solution, though they are capital- and energy-intensive.[125] Other options include liquefaction, which increases density but carries a high energy cost and risk of boil-off, and chemical carriers like ammonia that provide a high-density, long-term storage option leveraging existing infrastructure. Additionally, underground salt caverns offer a low-cost, bulk storage solution where geology permits, providing a diverse set of options to balance cost, safety, and supply flexibility.[126]

Pinpointing the single most cost-effective, long-term solution for these logistics remains challenging, as the ideal approach is heavily dependent on the hydrogen's final form and end-use application.[127] Therefore, the most viable strategy is a phased deployment that connects production hubs to demand centres through a multilayered approach, tailoring transportation and storage to the specific distance, volume, and end-use requirements of each project. Ultimately, a coordinated national plan that integrates these various technologies will be essential for building a robust and affordable green hydrogen economy in India.

Strategic Transportation & Distribution Cost Optimization

India's rising energy demand, robust renewable energy growth, and export ambitions call for a cohesive, future-ready infrastructure strategy. India must design a network that functions as the circulatory system of its green economy, where generation assets, transmission lines, pipelines, and ports serve as arteries delivering sustainable energy across regions and borders.

This strategy should integrate expansion of energy transmission, especially high-voltage direct current (HVDC), with modernization of natural gas networks and phased development of hydrogen, CO_2, ammonia, and methanol pipelines. Such comprehensive planning forms the backbone of a sustainable supply chain to maximize resource efficiency and reinforce India's global energy leadership.

Hydrogen blending in natural gas pipelines is under evaluation in Europe and India. However, hydrogen-induced cracking needs rigorous phased testing. Polymer pipelines or internal linings are globally being pursued as a safer alternative.

Government-industry partnership can establish integrated energy and storage corridors, combining HVDC lines and multi-product pipelines with connected storages. For example, Corridors from Rajasthan to North India and from Kutch to Saurashtra and South Gujarat can serve domestic and export markets, improve returns, and support multi-system, demand-driven hubs that produce and export green ammonia and methanol. Such efficient transport and storage systems can sharpen competitiveness under RFNBO emissions rules.

Achieving this vision requires regulatory foresight, legislative agility, and deployment of advanced technologies. Piloting new storage systems, evaluating commercial feasibility studies, and setting operational standards will enhance corridor flexibility.

KBC's Integrated Asset Modeling approach simulates thermodynamic and pressure-temperature conditions across energy and CO_2 value chains.[128] With such vision, integrated hydrogen value chain projects could reduce CapEx and OpEx projects by 30-70% while Bringing Decarbonization to Life® at scale.

Developing Scalable & Diverse Storage Solutions

India's hydrogen economy demands a storage portfolio as precise, predictable, and resilient as a high-performance supply chain, one tailored to fit generation hubs, energy corridors, and growing industrial hubs. A one-size-fits-all approach won't suffice; flexibility fuels the future of hydrogen.

Among the most immediate and accessible solutions is gaseous hydrogen, stored at 350–700 bar, is well-suited for short-term buffering but is limited in scale and very high in CapEx and OpEx.[129] Gaseous hydrogen in pipelines or blended in natural gas pipelines can be more scalable and cost effective, as it plays a dual role of strategic storage and transport.

For higher energy density and export potential, liquid hydrogen offers higher energy density, but liquefaction consumes about 30% of hydrogen's energy content.[130] Managing boil-off burdens, cryogenic challenges, and thermal threats demand advanced modeling, especially for industrial end users and export hubs.

Chemical carriers like ammonia offer an alternative. Ammonia excels in seasonal storage and long-distance transport. Its hydrogen density and handling familiarity make it attractive, but cracking for reconversion remains energy- and capital-intensive.

For long-duration, geological-scale storage, underground storage in salt caverns can be explored for long-term storage at competitive cost. However, India's geological constraints with limited salt dome formation pose a challenge to scaling this solution.[131]

Together, these technologies support a layered strategy, piped gas for daily demand, ammonia for monthly balancing, and underground reserves for seasonal or strategic stockpiling, can secure supply, stabilize markets, and cost control. Co-location and multi-system design across the hydrogen value chain is essential to improve system economics.

To accelerate this evolution, KBC supports these strategies via modeling and asset optimization as well as aligning infrastructure investments with policy objectives and demand trajectories across India's hydrogen value chain while Bringing Decarbonization to Life®.

4

STRATEGIC SECTORAL INTEGRATION & NEW APPLICATIONS

Beyond traditional industrial applications, green hydrogen holds immense potential for broader societal and economic impact. This section explores innovative uses, such as its role as a local community utility for decentralized energy, its contribution to climate-smart agriculture, and its capacity to enhance urban energy security and climate resilience. It aims to shed light on diverse, untapped opportunities for green hydrogen to serve varied needs across India.

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India's National Green Hydrogen Mission, launched in January 2023, is poised to transform the country's energy landscape and catalyse broad societal change. With a target of producing 5 million tonnes of green hydrogen annually by 2030 and an initial investment of ₹19,744 crore-including ₹17,490 crore for the Strategic Interventions for Green Hydrogen Transition (SIGHT) programme-this mission aims to decarbonise hard-to-abate sectors while creating new economic opportunities across urban and rural India.[132,133] Large-scale green hydrogen deployment will generate up to 600,000 direct and indirect jobs by 2030. Employment will span the entire hydrogen value chain: operators for gigawatt-scale electrolysers powered by solar, wind and small hydro; technicians for pipeline and storage maintenance; engineers and workers in electrolyser component manufacturing; and specialists in logistics infrastructure. Priority industries such as cement, steel and heavy transport will require significant upskilling. Cement plants retrofitted with carbon capture and methanol synthesis units will need process engineers to integrate low-carbon production pathways. In steelmaking, hydrogen-based direct reduction of iron ore will create demand for metallurgists and chemical engineers. In the transport sector, fuel-cell bus and truck fleets will drive growth in fuel-cell stack manufacturing, system integration and refuelling station construction.

To meet this demand, the Mission and the Ministry of Skill Development and Entrepreneurship have initiated training programmes covering green hydrogen plant technician, process engineer, electrolyser technology specialist (manufacturing and assembly), operations & maintenance head/manager, and system integration Specialist.[134] The Scheme for Harnessing and Injecting Projects (SHIP) have allocated ₹400 crore to research and development, training and certification, ensuring that workers meet rigorous technical and safety standards.

Beyond employment, green hydrogen offers significant public health benefits through improved air quality. Replacing fossil fuels in power, cement and steel production and heavy transport reduces particulate matter (PM2.5, PM10), sulphur dioxide, nitrogen oxides and carbon dioxide emissions. Regions such as Gujarat and Odisha, designated as hydrogen hubs, will experience measurable declines in hospital admissions for respiratory and cardiovascular conditions. The Mission's goal to cut 50 million tonnes of CO2 per year by 2030 and its allocation of ₹496 crore for hydrogen mobility pilots will alleviate healthcare costs that currently account for nearly 8 per cent of India's GDP.[67,132]

Green hydrogen also enables circular economy practices. Cement plants can convert captured CO_2 into methanol feedstock for PVC production, transforming a waste stream into a revenue source. Electrolyser and renewable energy equipment recycling programmes will recover critical minerals. Water-use challenges in electrolysis will be addressed by integrating wastewater recycling and renewable-powered desalination. Oxygen produced as a byproduct of electrolysis can supply hospitals and wastewater treatment facilities, further reduce waste and enhance system efficiency.

In rural and semi-urban areas, decentralised hydrogen production can overcome persistent power deficits. Solar- and wind-driven electrolysers coupled with fuel-cell microgrids will supply electricity to villages, schools, health centres, banks and telecom towers, replacing diesel generators and advancing India's electrification goals. In agriculture, hydrogen fuel cells can power tractors, irrigation pumps and harvesters, cut the sector's 4-5 billion-litre annual diesel consumption while lowering operating costs. Business models such as community cooperatives, public-private partnerships, micro-enterprise hydrogen services and Utility-as-a-Service subscriptions will ensure local ownership, financial sustainability and rapid scale-up. Green hydrogen will also support climate-smart agriculture. On-farm ammonia synthesis units can produce low-carbon fertiliser, reducing reliance on imported urea and transportation emissions. Hydrogen-powered cold chain solutions, off-grid refrigerated storage and transport, can prevent nearly one third of India's perishable produce losses, enhancing food security in climate-vulnerable regions.

Urban centres stand to gain resilience from hydrogen-based backup power and emergency systems. 100-bed facility hospitals can run critical life-support equipment for two days on 10-20 kilograms of hydrogen in fuel cells, while oxygen byproducts address medical supply shortages during grid failures caused by cyclones or heatwaves.[135,136] Data centres can maintain continuous operation and cooling through fuel-cell backups, avoiding costly outages. Telecom towers powered by compact hydrogen units ensure connectivity during natural disasters. Hydrogen fuel-cell buses and metro systems provide zero-emission transport and can supply emergency power to urban infrastructure.

Realising these applications requires coordinated policy support, infrastructure investment and skills development. Mandated consumption obligations tied to incentives will guarantee hydrogen demand and attract private capital. Upgrading power grids, establishing hydrogen transport corridors, constructing refuelling stations and integrating hydrogen production with renewable energy plants will build the physical backbone of the hydrogen economy. Collaboration between industry, academia and government will close the skills gap, ensuring that India's workforce is equipped to design, build and operate a safe, efficient and inclusive green hydrogen ecosystem. Through these strategic sectoral integrations and new applications, green hydrogen will deliver sustainable prosperity, energy security and climate resilience across India.

Maximizing Socio-Economic & Environmental Impacts

India's National Green Hydrogen Mission (NGHM) represents more than decarbonization, it is a catalyst for socio-economic transformation. With a target of 5 million tonnes annually by 2030 and investments of nearly ₹8 lakh crore, the sector could generate over 600,000 jobs across the value chain, from electrolyser operation and renewable energy generation to pipeline upkeep, storage, logistics, and manufacturing.

Priority sectors will see the most impact. In cement, hydrogen can enable CO_2-to-methanol conversion, requiring factory retrofits; in steel, hydrogen-based reduction methods will create demand for metallurgists and process engineers; and in transport, fuel-cell buses and trucks will open new roles in servicing, infrastructure, and manufacturing. This transition underscores the urgent need for a skilled workforce. NGHM, together with the Ministry of Skill Development and initiatives like SHIP, is investing in training, R&D, and certification to build sector-specific expertise and ensure safety standards.

The wider economic and environmental benefits are significant. Replacing fossil fuel imports with hydrogen could save India over ₹1 lakh crore annually by 2030, while cleaner air improves public health outcomes. Circular economy practices, such as CO_2 utilization and water reuse, further strengthen sustainability.

Challenges remain: high land and water requirements, weak power grids, limited hydrogen transport infrastructure, and investor uncertainty. Policy levers such as Green Hydrogen Consumption Obligations can de-risk private investment by guaranteeing demand. With the right combination of infrastructure, training, and policy support, green hydrogen can deliver a just, inclusive, and transformative energy transition for India.

Broader Benefits of Green Hydrogen Deployment

Beyond job creation and decarbonization, large-scale deployment of green hydrogen under the National Green Hydrogen Mission (NGHM) delivers far-reaching socio-economic and environmental benefits. By replacing fossil fuels in steel, cement, and heavy transport, hydrogen reduces key pollutants PM2.5, PM10, SO_2, NO_x, and CO_2 that drive respiratory and cardiovascular diseases. Regions like Gujarat and Odisha, emerging as green hydrogen hubs, would gain significantly from reduced pollution, while hydrogen-powered mobility in urban centers can lower hospital admissions and healthcare costs. With NGHM targeting annual reductions of 50 million metric tons of CO_2 by 2030 and allocating ₹496 crore to mobility pilots, the initiative directly supports improved air quality and reduced economic losses from pollution-related diseases, which currently account for nearly 8% of India's GDP.

Hydrogen deployment also fosters circular economy practices. Captured CO_2 in cement plants can be converted into methanol for PVC production, transforming waste into valuable feedstock. Electrolysers and renewable systems require rare earth elements, making recycling of decommissioned devices essential. NGHM's domestic manufacturing incentives can integrate recycling frameworks for electrolysers, solar panels, and batteries.

Water, another critical resource, can be managed through circular solutions such as wastewater recycling and renewable-powered desalination, ensuring sustainable hydrogen production in water-stressed regions. Electrolysis byproducts like oxygen can be valorized in healthcare and wastewater treatment, minimizing waste streams. Furthermore, hydrogen serves as a long-duration energy storage medium, absorbing surplus renewable power and improving overall system efficiency.

Together, these mechanisms establish hydrogen not only as a decarbonization tool but as a driver of public health improvement, resource efficiency, and long-term sustainability.

Green Hydrogen as a Local Community Utility

Green hydrogen offers transformative potential to meet decentralized energy needs in rural and semi-urban India, where energy access remains limited. Produced from solar, wind, or small hydropower, it can support the National Green Hydrogen Mission (NGHM) target of 5 million tonnes per year and 125 GW renewable capacity.

Local power generation is one avenue. Fuel cells linked to solar rooftops or microgrids can supply homes, schools, and health centers while replacing diesel in telecom towers and banks, supporting India's 100% electrification goal. For cooking, hydrogen-powered stoves and community kitchens reduce reliance on firewood and LPG, cutting indoor air pollution and deforestation. In agriculture, hydrogen-powered tractors, pumps, and harvesters provide small farmers with cleaner and quieter alternatives. With India consuming 4–5 billion liters of diesel annually, initial pilots in Punjab and Haryana show encouraging results.

Broader benefits include electrifying 25,000 unelectrified villages (advancing SDG 7), reducing women's and children's exposure to smoke, producing oxygen for hospitals and industries, enabling wastewater reuse, and creating rural jobs in operations and maintenance. This aligns with NGHM's goal of 600,000 jobs.

Scalable business models such as cooperatives, public–private partnerships, micro-enterprises, and utility-as-a-service approaches can play a key role in strengthening hydrogen adoption. Together, these approaches can deliver clean, reliable energy and inclusive rural development. [137,138,139,107]

Green Hydrogen's Role in Climate-Smart Agriculture

Green hydrogen holds transformative potential for making Indian agriculture climate-resilient by addressing challenges in energy use, fertilizer supply, and food preservation. Agriculture consumes nearly 5 billion liters of diesel annually, while relying heavily on fossil-fuel-based fertilizers and suffering significant losses due to inadequate cold storage.[140] Green hydrogen offers a practical pathway to decarbonize these systems while improving rural sustainability.

Localized green ammonia production through small-scale, renewable-powered units could supply farmers with low-emission fertilizers, reducing dependence on fossil-fuel-based urea. Such decentralized systems cut greenhouse gas emissions, lower transportation costs, improve crop yields, and provide greater resilience during supply chain disruptions.

Hydrogen can also replace diesel in agricultural machinery. Lightweight, fuel cell-powered tractors, irrigation pumps, and harvesters would provide small farms with cleaner, quieter, and more reliable alternatives, lowering both emissions and operating expenses. Importantly, hydrogen storage can secure uninterrupted energy for critical farming operations during peak periods or power outages.

Another critical application lies in cold chain logistics. India currently loses nearly one-third of its perishable produce due to insufficient refrigeration and transport. Hydrogen fuel cells can power cold storage units and refrigerated vehicles in off-grid and semi-urban areas, reducing post-harvest losses and enhancing farmer incomes. Cooperative management of such storage hubs could strengthen rural food security, especially in climate-vulnerable regions. Together, these applications align with national sustainability goals by reducing emissions, enhancing rural adaptation, and revitalizing farm economies. With the right policy incentives, training, and infrastructure, green hydrogen can form the backbone of a truly climate-smart agricultural system in India.

Enhancing Urban Climate Resilience with Green Hydrogen

Green hydrogen can play a pivotal role in enhancing urban energy security and disaster resilience in Indian cities, where rising energy demand, unstable power distribution, and intensifying climate emergencies pose escalating risks. Produced through renewable-powered electrolysis, hydrogen provides clean, flexible, and storable energy that safeguards critical infrastructure during crises.

Hospitals require uninterrupted power, yet Cyclone Tauktae disrupted operations in 70% of facilities in one city. Hydrogen fuel cells can maintain a 100-bed hospital for two days with just 10–20 kg of hydrogen, while oxygen produced as a byproduct supports medical supply needs.[135,136] Similarly, data centers, responsible for India's digital economy, are highly vulnerable to power outages during heatwaves. Hydrogen backup systems can ensure continuous operation and cooling, reducing both downtime losses and emissions.

Telecom towers, essential for emergency communication, typically rely on diesel. Compact 5 kW hydrogen units can sustain a tower for 24 hours, ensuring connectivity during disasters. In transport, hydrogen buses and metro backup systems offer reliable zero-emission mobility, with ranges of 300–400 km per fill, while doubling as emergency power sources.

System-level benefits are equally critical: hydrogen substitution for diesel and biomass reduces PM2.5 and NOx pollution, improving urban air quality and public health. For implementation, NGHM's SIGHT scheme can lower costs for hospitals, transit, and data centers, while SHIP-supported public-private partnerships enable retrofits in disaster-prone cities like Mumbai, Kolkata, and Delhi. Local hydrogen hubs and workforce training via ITIs and universities will further support deployment. Integrating hydrogen into urban emergency preparedness strategies can ensure resilient, low-carbon cities capable of withstanding future climate shocks.

5

INNOVATION ECOSYSTEM & R&D COMMERCIALIZATION

A robust innovation ecosystem is the bedrock of long-term green hydrogen leadership and India's global competitiveness and self-reliance. Herein, this section discusses strategies to effectively bridge the "lab-to-market gap" for green hydrogen technologies, emphasizing frameworks for successful institutional R&D and tailored support mechanisms for Indian startups and research labs. Insights also explore how market understanding can guide R&D priorities to ensure commercial viability and rapid adoption.

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A strong and open research ecosystem, bringing together major industries, academic institutions, and startups, is essential to transforming green hydrogen from lab concepts to real-world solutions. The National Hydrogen Mission (NGHM) demonstrates this commitment through substantial allocations, ₹1,466 crore for pilot projects and ₹400 crore for research and development (R&D), enabling established players and innovators alike to collaborate and progress.[107]

The Mission strategically promotes key enablers and leverages the expertise of leading research institutions.[141,142,143] A major initiative under this effort is the Strategic Hydrogen Innovation Partnership (SHIP), a public-private framework designed to make green hydrogen production, storage, and use more affordable and reliable. Supported by industry, government, and potential venture capital, SHIP seeks to derisk early-stage technologies through consortium-led partnerships, including emerging ventures.[107] Funding schemes like NGHM's R&D program and the Department of Science & Technology's Hydrogen Research Initiative boost institutional research and startups, focusing on pilot projects in sectors such as low-carbon steel, long-haul mobility, decentralized energy, and advanced electrolyzers and fuel cells.[107,144,145] Notably, direct support has helped indigenous startups develop technologies like hydrogen sensing, reflecting the agenda's focus on domestic modular electrolyzers, advanced hydrogen tanks, and efficient PEM fuel cells.[146]

Active collaboration between academia and industry drives many efforts. IIT Delhi partners with NTPC to pilot green hydrogen for ammonia production.[147] In steel, the Ministry of New and Renewable Energy has approved pilot (~40-50 TPD plant capacity) projects involving Matrix Gas with IIT Bhubaneswar and Simplex Castings with IIT Bhilai, likely to be commissioned in next 2-3 years.[65] Moreover, Vedanta has also partnered with IIT Bombay to develop technology for producing green steel using hydrogen.[54] On blending green hydrogen to the natural gas and its effect on the existing infrastructure, GAIL is conducting joint studies with Engineers India Limited (EIL) and IIT Kanpur, and Oil India Limited (OIL) with IIT Guwahati.[93,148] ONGC Energy Centre (OEC) has also partnered with various institutions, such as the Institute of Chemical Technology (ICT) in Mumbai on copper-chlorine cycle technology for hydrogen generation at 25 LPH and IIT Delhi on iodine-sulfur thermochemical cycles for 300 LPH production, to develop thermochemical processes for producing hydrogen.[149,150] Additional projects include solid oxide electrolyzers at HPCL, at its HP Green R&D Centre, Bengaluru, (produces 99.99% pure hydrogen using 20-30% less energy) and Vanadium Redox Flow Battery energy storage by ONGC with IIT Madras and High Energy Batteries (HEB), Trichy.[149,151] Additionally, the Indian Institute of Petroleum and Energy (IIPE), Visakhapatnam and NTPC have a pilot project to produce green hydrogen from desalinated water, and researchers at NITK Surathkal are focused on a project to produce it from seawater, a cost effective and safe process, requiring minimal pretreatment.[152,153] IIT Delhi developed a novel hydrogen fuelled spark-ignition engine generator in collaboration with the Indian Oil R&D Centre and Kirloskar Oil Engines Limited (KOEL) for the utilization of hydrogen in internal combustion engines for zero-emission with higher thermal efficiency.[154] Moreover, researchers from IIT Mandi, IIT Delhi, and Yogi Vemana University has replicated the structure of the leaf in an economical inorganic catalyst for light-induced production green hydrogen and ammonia.[155,156] IIT Madras is conducting certification courses on hydrogen technology and has partnered with Zemblance Hydrocarbons for specialized training programs.[134] A list of initiatives by leading institutions across the sector of green hydrogen have provided elsewhere.[157]

Beyond domestic efforts, international collaboration is actively strengthening research networks and driving joint technology development. Recent examples include the India EU joint call focusing on "Waste to Green Hydrogen" and the Indo French call for "Green Hydrogen Innovations for Sustainable Energy Solutions," where DST provides Indian partners with up to ₹2.25 crores (approximately €250k) for a three-year project.[158,159] HPCL has partnered with the University of Birmingham, UK to develop hydrogen dispensing systems for revolutionising India's transport sector.[160] Such initiatives connect Indian researchers with global expertise and ensure research meets industrial needs. Alongside these existing global partnerships, keeping a close eye on breakthrough R&D in the green hydrogen ecosystem will inform more relevant collaborations and accelerate technology transfer. To stay at the forefront, India must monitor and adopt breakthrough R&D such as single-atom catalysts on atomically thin supports in South Korea and China, which offer ultra-efficient water electrolysis, and the China-Italy teams' room-temperature, light-driven heterolytic H_2 splitting with more than 99 percent CO_2-to-ethane selectivity.[161,162] Scaling up domestic pilots like the VOC Port project will require cost efficiencies, clear bunkering regulations, resilient supply chains, and corrosion-proof equipment, all supported by coordinated feasibility studies and technology transfer.[163] In the same spirit, the Provaris–Baker Hughes partnership combines H2Leo and H2Neo carrier designs with advanced compression systems to create scalable marine hydrogen logistics, showing how early adoption of global innovations can help India become a leader in the hydrogen economy.[164]

Startups play a vital role in advancing affordable, scalable technologies. Newtrace is bringing down electrolyzer costs by up to three-fold with its patent-pending, membrane-less design that cuts core components by 70 percent, uses earth-abundant catalysts and 3D-printed parts, and includes real-time management software.[165] Hygenco is building India's first green hydrogen plant in Hisar and already owns and operates facilities in Haryana and Maharashtra, offering end-to-end techno-commercial solutions for clean energy and transport.[59] Matrix Gas & Renewables plans to invest ₹35 billion over three years to develop 1,000 MW of green hydrogen capacity, including a 50 TPD steelmaking pilot, India's first hydrogen valley in Pune and electrolyzer manufacturing under the PLI scheme with Gensol Engineering.[166] Their efforts complement those of established companies, all advancing hydrogen projects across sectors.

While progress is commendable, opportunities remain to broaden participation beyond traditional academic institutions, engaging more private sector research capacity.[143] A broader global perspective reveals the scale of international investment, with growing international investments, $13.5 billion in the USA, $6.7 billion in China, $5.2 billion in the European Union and $50 billion in the Gulf region, India aims to leverage its capabilities, ensuring a coordinated approach to R&D, commercialization, and the buildout of a resilient, homegrown hydrogen economy.[167] Establishing clearer pathways for their involvement, coupled with robust, transparent monitoring strategies, could significantly diversify and strengthen research efforts, fostering a more inclusive innovation landscape. Furthermore, as hydrogen applications expand into new domains, continuous and proactive R&D into enhancing safety measures and hydrogen handling technologies becomes increasingly vital. Beyond advancements in electrolyzers, production components, fuel cells, transportation, and storage, dedicated scientific inquiry into robust safety protocols, advanced leak detection systems, and innovative materials for secure containment is paramount. This specialized focus would proactively address the inherent complexities of hydrogen handling, thereby enhance confidence and accelerate widespread adoption across industries. These evolving areas, bringing in more research players and strengthening safety measures, offer clear paths for policy makers and R&D leaders to focus on.

Along with continued funding and support, paying attention to these practical implementation details will be essential for building a comprehensive, safe, and successful green hydrogen economy in India.

This opinion explores practical frameworks, investment strategies, and monitoring approaches that help institutional R&D bridge the lab-to-market gap; tailored support mechanisms like funding, incubation, and mentorship to empower startups and labs; the role of real-time market intelligence in guiding R&D toward commercially viable solutions; and the value of strong academic-industry partnerships in driving India's energy independence, global competitiveness, and export ambitions.

Ensuring Institutional R&D Success & Market Integration

Commercializing Green Hydrogen R&D: A Strategic Framework could comprise of;

Practical R&D Roadmap

- ***Market Alignment & TRL:*** Specific market needs and applications may be defined for green hydrogen before starting R&D, with ongoing refinement throughout the project. Projects could be mapped by their Technology Readiness Level (TRL) to guide funding from lab (TRL 1–3) to pilot (TRL 4–6) and to scale-up (TRL 7–9).
- ***Flexible Funding:*** Early-stage grants and tax incentives could support initial R&D, followed by venture capital and industry private equity for commercialization under structured monitoring.

Strategic Investment

- ***Diversified Capital:*** Engage with private investors, VCs, and corporates with derisking tools (e.g., green bonds, tax credits) to reduce reliance on public funds, along with mechanisms and policies possibly involving financial incentives.
- ***Public-Private Partnerships:*** Fostering collaboration among industry, academia, and government to accelerate innovations and deployment.

Performance Monitoring

- ***KPIs & Feedback:*** Track hydrogen cost, efficiency, emissions, and job creation. Establish regular feedback loops with industry partners and end-users to ensure that research outcomes are relevant and meet real-world needs.
- ***Digital Verification:*** Application of blockchain and smart MRV tools to ensure transparency and compliance with environmental standards.

Bridging Lab to Market

- ***Pilot Projects:*** Funding pilot projects might demonstrate validity, scalability, and commercial potential, while mechanisms could be developed to transfer research results to industry.
- ***Market Development:*** Mechanisms to Create demand via procurement policies, infrastructure investment, and public awareness campaigns.

A streamlined, market-driven, and collaborative approach, supported by smart funding and robust metrics, is key to turning green hydrogen R&D into commercial success.

Targeted Support for Indian Startups & Labs

To effectively support Indian startups and research institutions in advancing green hydrogen technologies, a comprehensive, multi-pronged support framework comprising of following elements need be implemented:

Targeted Funding Support

- ***Grants and Subsidies:*** Provide dedicated government funding for R&D through grants, subsidies and incentives for venture capital and private equity investments.
- ***Startup Enablement:*** Facilitate early-stage support via incubation and acceleration programs offering financial and technical assistance.

Incubation, Mentorship, and Networking

- ***Green Hydrogen Incubators:*** Establish specialized incubation centers with domain-specific infrastructure and expertise.
- ***Mentorship & Ecosystem Connectivity:*** Enable mentorship by connecting startups with industry veterans, researchers, and investors. Promote collaboration through targeted networking events and industry-research linkages.

Public-Private Partnerships (PPPs) and Collaboration

- Promote joint R&D initiatives between academia, government, and industry to drive innovation and ensure smooth technology transfer from research labs to commercial entities.

Testing Infrastructure and Technical Facilities

- Develop shared facilities such as pilot plants and specialized labs for technology validation and prototyping.
- Invest in robust green hydrogen infrastructure, including production, storage, and distribution networks.

Regulatory Processes and Policy Reforms

- Streamline approval mechanisms and introduce green hydrogen–focused regulatory frameworks, tax benefits, and compliance simplifications.
- Enable open data sharing among stakeholders to foster transparency, innovation, and evidence-based policymaking.

Green hydrogen initiatives worth an estimated ₹2,00,000 crore are under implementation in the country with nine R&D and demonstration plant under construction and four already commissioned by major oil companies.[168]

By operationalizing these tailored mechanisms, India can cultivate a robust green hydrogen innovation ecosystem. This will also accelerate, scale-up and commercialization of technologies, supporting both energy security and national climate goals.

Leveraging Market Insights for R&D Prioritization

To accelerate green hydrogen innovation and commercialization R&D must be closely aligned with market dynamics.

- **Understanding Market Needs:** A comprehensive assessment of industry trends, regional regulations, and sector-specific demands, such as in transportation, industrial use, and energy storage, could help identify high-potential applications. Recognizing gaps in current hydrogen infrastructure and unmet technological needs is essential for targeted innovation.
- **Strategic R&D Prioritization:** R&D efforts should focus on areas that directly address market pain points, with emphasis on domestic modular electrolyzers, advanced hydrogen storage systems (Type III/IV cylinders), and efficient PEM fuel cells.
- **Closing Technological Gaps:** Innovation should center on improving the efficiency, scalability, and affordability of green hydrogen production, storage, and transport. Emphasis on materials research and system integration can resolve challenges like intermittent renewable input and infrastructure limitations.
- **Commercial Viability:** Technologies must be economically scalable and adaptable to evolving market needs. Conducting financial viability assessments and fostering industry partnerships ensures sustainable deployment pathways.
- **Digital Integration:** Leveraging AI and robotics enhances production optimization, real-time monitoring, predictive maintenance, and material discovery, accelerating development cycles and boosting safety.
- **Collaboration & Policy Support:** Cross-sector collaboration between government, industry, and academia, alongside supportive policies and incentives, is critical to drive innovation and infrastructure scale-up.

By embedding market intelligence into R&D strategy, India can fast-track the development of competitive, scalable green hydrogen technologies, paving the way for a robust hydrogen economy.

Strategic Impact of Academic-Industry Synergy

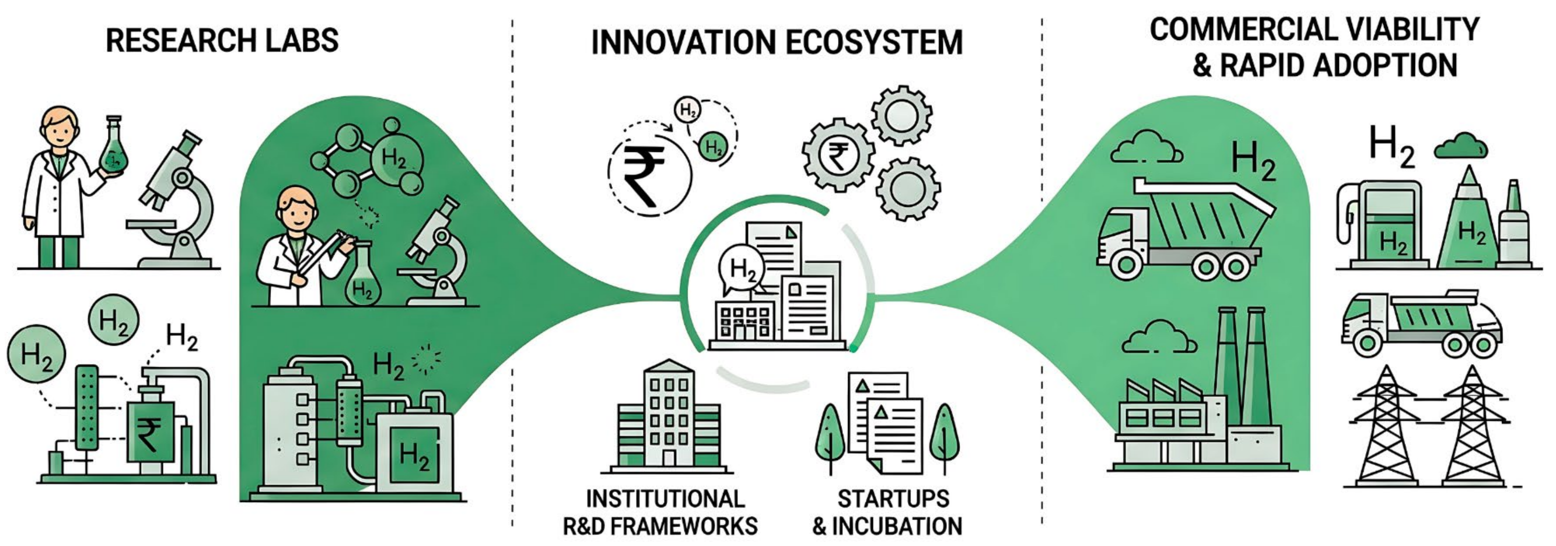
Strengthening collaboration between academia and industry is pivotal to advancing India's green hydrogen mission, enabling the country to achieve energy independence by 2047 and emerge as a global leader in the green energy supply chain. This synergy can fast-track technological innovation, reduce costs, and scale up production, ultimately supporting substantial exports of green hydrogen and its derivatives.

Key Enablers of Collaboration:

- **Public-Private Partnerships (PPPs):** Establish co-investment platforms where academia, industry, and government jointly fund R&D, pilot projects, and technology commercialization.

- **Joint Research and Innovation Hubs:** Create dedicated centers to foster collaboration among researchers, engineers, and policymakers on cutting-edge hydrogen technologies.
- **Shared Resources and Expertise:** Facilitate access to specialized research facilities and promote the exchange of knowledge to bridge academic research and industrial application.
- **Targeted Collaborative Projects:** Focus on key areas such as advanced electrolyzer efficiency, low-cost production techniques, and innovative storage and utilization solutions.
- **Skilling and Training Programs:** Develop industry-academia training initiatives to ensure a robust talent pipeline for green hydrogen sectors
- **Policy and Regulatory Support:** Implement conducive policies, including tax incentives, funding schemes, and regulatory simplification, to support collaborative innovation
- **Standards and Certification Frameworks:** Jointly develop robust standards and certification processes to ensure product quality and global market access.

This integrated approach will accelerate innovation, drive down costs, enhance India's export competitiveness, and secure long-term energy resilience.



6

INVESTMENT MOBILIZATION & FINANCIAL DE-RISKING

Attracting significant capital is crucial for scaling India's ambitious green hydrogen journey. This section delves into innovative and blended financing models designed to de-risk investments for diverse projects, including smaller or pioneering ventures. It examines how enhanced market transparency and data mechanisms can boost investor confidence, unlocking the substantial capital required for the sector's rapid growth and diversification.

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The global shift towards sustainable development, renewable energy, and climate-resilient infrastructure requires unprecedented levels of investment and courage for investment from the investors. According to the International Energy Agency (IEA), clean energy investment alone must triple to USD 4 trillion annually by 2030 to achieve net-zero targets.[169] However, mobilising such capital from investors eyeing short-term returns may hinder the entire process. Further, long-term investments are constrained by perceived risks, the high cost of capital in emerging economies, and limited financial instruments that align private incentives with public goals. Against this backdrop, investment mobilisation and financial de-risking have become central strategies for bridging financing gaps, particularly in developing and transition economies.

The Role of Investment Mobilisation

Investment mobilisation refers to the process of attracting and channelling public, private, and blended finance towards targeted development outcomes. It involves not only scaling financial flows but also directing them to underfunded sectors such as renewable energy, sustainable agriculture, and climate adaptation.[170] Globally, public funds are often insufficient; hence, the strategic role of multilateral development banks (MDBs), sovereign wealth funds, and institutional investors is crucial. For instance, the World Bank's Climate Investment Funds have leveraged USD 8.3 billion in donor funds to mobilise over USD 60 billion in co-financing.[171] Such leverage demonstrates how well-structured financing frameworks can attract large-scale private capital.

Understanding Financial De-risking

Financial de-risking encompasses a range of instruments and mechanisms designed to reduce actual and perceived risks for investors. Risks may include political instability, regulatory uncertainty, currency volatility, or technology adoption challenges.[172] De-risking mechanisms include guarantees, concessional loans, first-loss capital, political risk insurance, and hedging instruments. For example, the Multilateral Investment Guarantee Agency (MIGA) provides political risk insurance that enables private firms to invest in fragile contexts.[173] Similarly, blended finance models, where concessional public funds absorb part of the risk, are increasingly deployed to attract private sector participation in high-impact but high-risk projects.

Global Trends in De-risking

Globally, de-risking has emerged as a critical enabler for renewable energy transitions. In Sub-Saharan Africa, where financing costs are among the highest, initiatives such as the Africa Renewable Energy Initiative combine grant funding with risk-mitigation instruments to crowd-in private investors.[174] In Asia, India's use of viability gap funding and sovereign guarantees has accelerated solar and wind capacity growth, attracting foreign investment despite market risks.[175] At the same time, OECD countries are expanding green bonds and sustainability-linked loans, providing long-term financing that lowers risk premiums for climate-aligned projects.[176]

Challenges and Critiques

Despite progress, significant challenges remain. Critics argue that financial de-risking may lead to the socialisation of risks and privatisation of profits, whereby public funds disproportionately protect private investors.[177] Moreover, de-risking strategies often focus narrowly on financial risks without addressing structural barriers such as weak governance, institutional capacity, and social inequalities. Mobilisation efforts also face geographic imbalances: while renewable energy investments are growing in advanced economies, emerging markets, where the need is greatest, still attract less than 20% of global clean energy finance.[178]

Policy Implications

To scale investment mobilisation and improve the effectiveness of de-risking, global cooperation is essential. MDBs or regional economic cooperative bodies like SAARC, BRICS must move from direct lending towards risk-sharing instruments that unlock private capital at scale. Countries should establish stable policy environments, transparent regulatory frameworks (not just a formulaic measurement), and robust financial markets to reduce underlying risks. Innovative instruments such as sustainability-linked bonds, climate risk insurance pools, and digital finance platforms offer additional pathways to enhance mobilisation.[171] Importantly, de-risking must be embedded within broader just transition frameworks, ensuring that mobilised investments create inclusive, equitable, and sustainable outcomes.

Investment mobilisation and financial de-risking are indispensable for meeting global development and climate goals. They represent complementary strategies: mobilisation focuses on scale, while de-risking ensures risk-adjusted returns that attract private participation. To be effective, both must be designed to balance investor confidence with principles of expanding risk sheet, social equity, align with national priorities, and deliver long-term sustainability. The global experience demonstrates that when structured effectively, these mechanisms can catalyse transformative change, turning financial risks into opportunities for resilient and inclusive development.

7

POLICY & REGULATORY ENABLEMENT (UNDERSTANDING THE LANDSCAPE FOR STAKEHOLDERS)

An adaptive and coherent policy environment is vital for seamless green hydrogen deployment across India. This section provides insights into how existing policy and regulatory frameworks can be understood and navigated to support market mechanisms. It explores mechanisms for de-risking investments through clear policy guidance and the importance of regulatory harmonization across states, all crucial for stakeholders operating within this evolving landscape.

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India stands at a pivotal moment in its energy transition journey, with green hydrogen emerging as a cornerstone of its decarbonization and energy self-reliance strategies. The launch of the National Green Hydrogen Mission (NGHM) in 2023 marks a significant commitment by the Government of India to develop a robust green hydrogen ecosystem, aiming to make the country a global hub for hydrogen production, utilization, and export. With an outlay of ₹19,744 crore, the mission is designed to create a framework for scaling up demand and supply, catalyzing investments, and fostering innovation across the hydrogen value chain.[132,133]

As hydrogen applications expand into mobility, industry, and power generation, the need for a supportive policy and regulatory environment becomes critical. The success of green hydrogen depends not only on technological breakthroughs but also on the ability to reduce risks for investors and streamline implementation. Given that hydrogen intersects with multiple sectors, energy, transport, industry, waste management, and chemicals, it requires coordination across central and state governments, financial institutions, safety regulators, and market platforms.

Key regulatory interventions such as Green Open Access Rules (2022) now enable hydrogen producers to procure renewable power more affordably, directly supporting decentralized and off-grid hydrogen generation.[179] At the same time, the Bureau of Energy Efficiency (BEE), in collaboration with MNRE, is leading the development of a carbon-intensity-based certification scheme, essential for tracking, verifying, and trading green hydrogen and its derivatives in domestic and international markets.[180]

However, the landscape remains fragmented. Developers and investors must navigate a complex matrix of inter-state and intra-state regulations, ranging from land acquisition and environmental clearances to safety standards and power banking rules. Initiatives like the PM Gati Shakti Master Plan are helping integrate spatial and infrastructure planning to enable hydrogen logistics and distribution networks, but implementation still varies widely across jurisdictions.

Adding to this, market mechanisms such as hydrogen exchanges, demand aggregation models, and certification systems are still evolving. While institutions like the Central Electricity Regulatory Commission (CERC) and platforms like Indian Energy Exchange (IEX) are exploring hydrogen-related trading mechanisms, the absence of a dedicated hydrogen market restricts price discovery and investor confidence.[107,181]

Furthermore, India's hydrogen strategy places special emphasis on supporting smaller ventures, decentralized projects, and new use cases, segments that often face higher capital and operational risks. For such players, targeted policy tools like Production-Linked Incentives (PLI), Viability Gap Funding (VGF), and credit guarantees can be game changers, helping reduce perceived risks and improve bankability.[107]

In this context, understanding and navigating the evolving policy and regulatory frameworks is not just a compliance requirement but a strategic necessity. This section of the report delves into the core policy enablers, investment de-risking mechanisms, and harmonization strategies that can unlock the potential of green hydrogen in India, ensuring that it becomes an inclusive, scalable, and competitive part of the nation's energy future.

Understanding Adaptive Policy Frameworks

The National Green Hydrogen Mission (NGHM) lays the foundation for an enabling landscape for development of market intelligence systems and potential trading platforms for green hydrogen, aligning with the country's broader decarbonization goals. The NGHM promotes demand aggregation, price discovery, and institutional frameworks that can support real-time data collection and market development.[107]

To enable and efficient infrastructure for green Hydrogen generation, the regulations under the Electricity Act and Green Open Access Rules (2022) facilitate renewable energy procurement for hydrogen production, encouraging transparent, multi-party transactions, essential for future exchange-based trading. The Bureau of Energy Efficiency (BEE), in collaboration with MNRE, is developing a carbon intensity-based certification system, enabling standardized tracking and valuation of hydrogen products, crucial for building digital registries and trusted markets.[179]

Efforts by CERC and existing platforms like IEX are exploring hydrogen-related trading mechanisms, potentially extending the current power exchange infrastructure to include green hydrogen or hydrogen certificates. Additionally, infrastructure initiatives like the PM Gati Shakti Master Plan support data-driven spatial planning, contributing to geo-intelligence for supply-demand coordination.[182]

Think tanks such as NITI Aayog, TERI, and CEEW are also contributing policy models, simulation tools, and stakeholder engagement strategies that promote adaptive policymaking. The regulatory frameworks are designed with flexibility through phased implementation, technology-neutral mandates, and stakeholder feedback mechanisms, allowing for mid-course corrections.

However, challenges such as the absence of a dedicated hydrogen exchange and limited price discovery mechanisms persist. Addressing these will require a unified National Hydrogen Data Platform, pilot trading programs, and robust certification systems to ensure transparency and investor confidence in a rapidly evolving hydrogen market.

De-risking Investments through Policy Clarity

To de-risk investments in green hydrogen, especially for emerging applications, decentralized production models, and smaller ventures, India must adopt a blend of enabling policy frameworks and targeted financial incentives. The National Green Hydrogen Mission already lays the foundation with a ₹19,744 crore outlay, but scaling success requires more granular support mechanisms.

Policy interventions that are most impactful include:

- **Implementation of pilot scale projects and continual support for R&D** as laid out in Phase 1 of the NGHM, which allows new applications to showcase and adapt to the existing market.
- **Priority grid access and open access mechanisms** for renewable electricity used in hydrogen production, which can significantly reduce input costs.
- **Standardized green hydrogen purchase obligations (GHPOs)** across sectors like refining, steel, and fertilisers to ensure predictable demand.

- Streamlined clearances and uniform regulatory norms across states to support distributed and small-scale units, which often face bureaucratic delays.

On the financial side, the following targeted incentives are crucial:

- **Viability Gap Funding (VGF) and Production-Linked Incentives (PLI)** tailored to smaller capacity electrolyzers and modular hydrogen units can reduce capital expenditure burdens for start-ups and MSMEs.
- **Interest subvention schemes and credit guarantee** from public financial institutions will help mitigate the risk perception among banks and investors, especially for decentralized systems in remote areas.
- **Innovation-linked grants and technology co-development** funding should be expanded, supporting R&D in newer hydrogen applications (e.g., mobility, decentralized ammonia, hydrogen microgrids).

Finally, mechanisms like hydrogen certification standards, carbon trading credits, and market-based auctions for offtake (similar to solar/RE) can create a transparent and predictable market ecosystem, attracting long-term private investment into high-risk segments of the green hydrogen value chain.

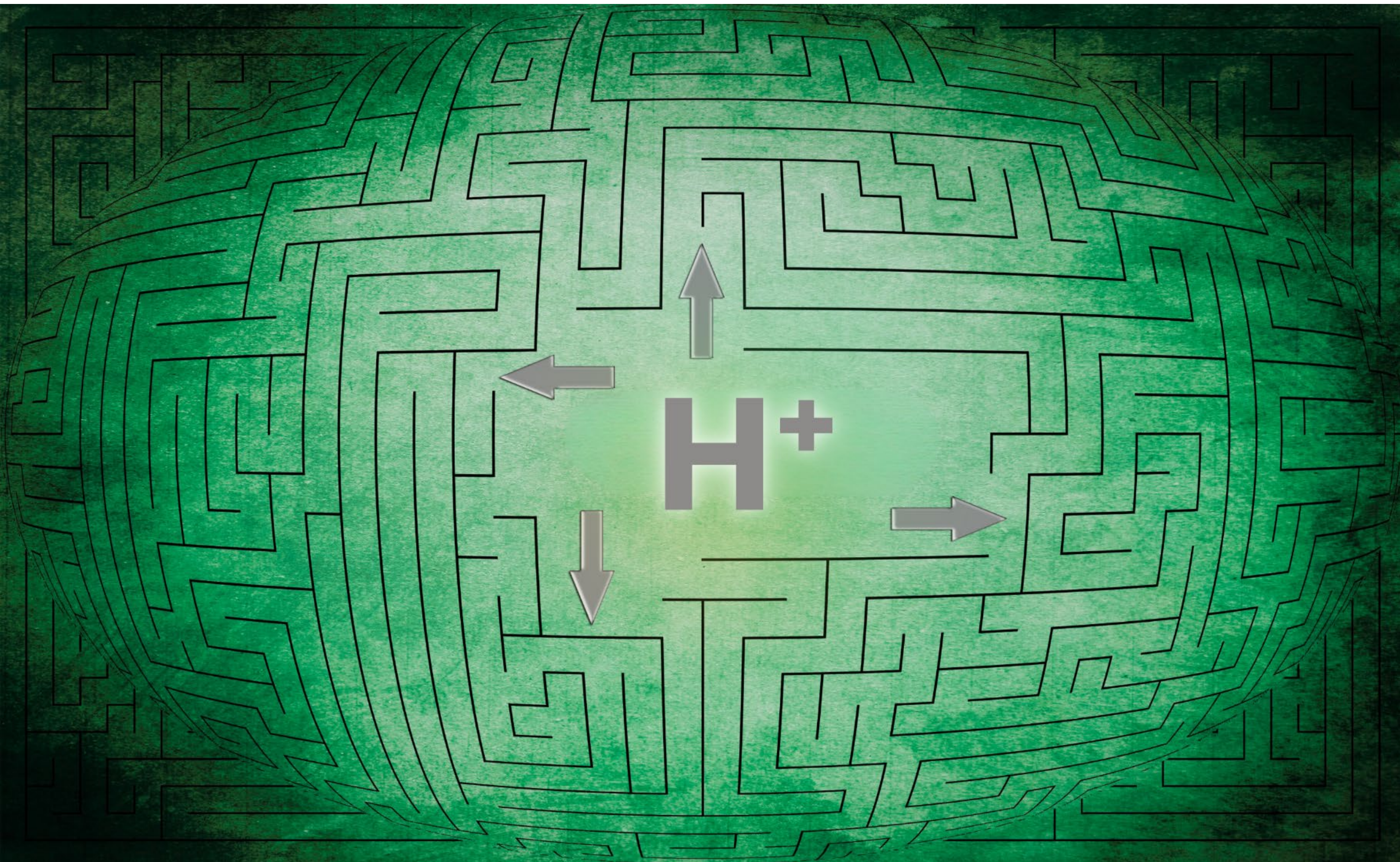
Streamlining Regulatory Harmonization

Navigating inter-state and intra-state regulations is critical to facilitating green hydrogen project development and ensuring smooth distribution across India. Due to the cross-sectoral nature of hydrogen, spanning energy, industry, and environment, developers must align with diverse and often fragmented regulatory frameworks.

- **Land Acquisition and Zoning:** Land laws vary significantly across states. Developers must coordinate with state industrial development corporations and local authorities for clear land-use classification (especially for RE-integrated hydrogen hubs). Central government support through land banks and plug-and-play industrial parks can ease access.
- **Environmental Clearances:** Hydrogen projects involving electrolysis may be considered low impact, but co-located biomass/waste-to-hydrogen plants or those using fossil fuels with CCS may trigger more stringent assessments. Streamlined single-window clearance mechanisms (such as the PARIVESH portal) and early-stage environmental impact studies are essential.
- **Safety and Handling Standards:** Safety protocols for hydrogen production, storage, and transport must comply with the Petroleum and Explosives Safety Organisation (PESO) guidelines and BIS standards. Inter-state consistency in enforcement, training of local regulators, and early engagement with the Chief Inspector of Factories and state-level PESO offices can avoid compliance delays.
- **Cross-Border and Inter-State Hydrogen Trade:** Regulatory frameworks for open access to power, Hydrogen trade, and inter-state pipeline development are still evolving. Developers should track policies under the National Green Hydrogen Mission and consult

state electricity regulatory commissions (SERCs) for power banking, transmission charges, and potential green hydrogen offtake mandates.

Engaging with central agencies like MNRE, DPIIT, and state renewable energy development authorities early in the project lifecycle enables alignment and de-risks project timelines. Institutional coordination and regulatory harmonization will be key to unlocking India's green hydrogen economy.



8

IMPLEMENTATION & ROADMAP (INSIGHTS FOR MARKET PARTICIPANTS)

Effective implementation is key to translating the national green hydrogen vision into reality on the ground. This final section outlines a comprehensive, phased roadmap offering critical insights for market participants. It delves into the establishment of robust market intelligence systems and potential exchanges, alongside the strategic development of green hydrogen hubs and production capacity. Furthermore, it covers the trajectories for integrating domestic demand through mandates, indigenizing the entire value chain, and establishing India as a leading global exporter through dedicated infrastructure and international partnerships. The discussion highlights key milestones and crucial cross-stakeholder collaborations necessary to ensure coordinated and efficient progress towards India's ambitious green hydrogen targets, benefiting all participants.

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India's transition to a low-carbon economy has brought the National Green Hydrogen Mission (NGHM) to the forefront as a strategic lever to meet climate targets, enhance energy security, and unlock new economic opportunities. Approved by the Union Cabinet in January 2023, the Mission reflects India's ambition to become a global hub for green hydrogen production, utilization, and export. It aims to establish a production capacity of at least five million metric tonnes per annum of green hydrogen by 2030. With an estimated investment potential exceeding eight lakh crores, the Mission is envisioned to not only decarbonize hard-to-abate sectors like refineries, fertilizers, steel, and heavy transport, but also to position India as a competitive player in the rapidly emerging international hydrogen market.

Despite this ambitious vision, India's green hydrogen ecosystem is still in its early stages. Several pilot projects and tenders have been announced, and public and private sector players are expressing strong interest. Yet, the sector remains fragmented. Key challenges include high production costs, limited exposure to domestic manufacturing of balance of plant systems and other critical equipment, and a lack of robust infrastructure for storage, transport, and distribution. Additionally, market mechanisms for offtake agreements, pricing, and financing are not yet mature. Many states have declared their intent to become green hydrogen hubs, but coordinated planning at the national level is needed to avoid duplication of efforts to prevent inefficiencies and demonstrate synergies.

In this evolving scenario, developing a clear, actionable, and time-bound roadmap is essential for translating the Mission's objectives into measurable outcomes. A top priority is establishing comprehensive market intelligence systems. Reliable, transparent data on production costs, demand projections, price trends, and supply chain capacities will help investors, policymakers, and industries make informed decisions. A well-functioning market intelligence framework will enable stakeholders to make informed decisions and build bankable projects that can attract domestic and international financing at scale.

Strategic expansion of ecosystem capacity must go hand in hand with accurate market data. Green hydrogen depends on the seamless integration of renewable energy supply, electrolyzer, storage, and distribution networks. Building this capacity in phases aligned with realistic demand growth helps avoid bottlenecks or stranded assets and ensures that investments deliver value. Pilot projects can generate critical learnings that inform the scale-up strategy and support the development of standards and best practices for safe design.

Another vital aspect that a clear roadmap must address is the need for strong global partnerships. Green hydrogen is inherently a globally traded commodity, and India's ambition to export hydrogen and derivatives like green ammonia centers on building trust and credibility in international markets. Transparent policy frameworks, predictable pricing structures, and a track record of reliable supply and after sales service support will be key to forging long-term offtake agreements with other countries. Collaborative ventures with global technology providers, research institutions, and financial partners can accelerate technology deployment, lower costs through economies of scale, and open new market access channels.

Ultimately, the success of the National Green Hydrogen Mission pivots on coordinated action among government bodies, industry players, financial institutions, and research organizations. A credible roadmap can clarify roles and responsibilities, set realistic milestones, and establish transparent monitoring mechanisms. This collective clarity is essential for attracting sustained investment and fostering confidence among domestic and global stakeholders.

In summary, India's green hydrogen mission holds immense promise to drive clean industrial growth and energy security. But its success depends on strong market intelligence, strategic capacity expansion, local value chain development, and robust global partnerships all supported by a clear and actionable implementation plan. By getting this right, India can emerge as a key player in the global green hydrogen economy and make a significant contribution to a sustainable future.

Phased Implementation Insights for Market Mechanisms

The National Green Hydrogen Mission has laid the foundation for India's green hydrogen economy, but turning vision into reality demands clear, phased, and collaborative implementation steps. A robust market intelligence system and the development of hydrogen exchanges are vital enablers to attract investments, manage risks, and ensure transparent price discovery.

What would be clear and phased roadmap:

Short-Term (0–2 years):

- ***Baseline Mapping:*** Conduct nationwide mapping of current and planned hydrogen produciton capacities, renewable feedstock, storage, and industrial demand clusters.
- ***Standardize Data:*** Mandate reporting on production, carbon intensity, and price trend
- ***Pilot Digital Dashboard:*** Launch an open-access platform showing aggregated supply, demand, price trends, carbon intensity.
- ***Industry Data Consortium:*** Formalize data-sharing agreements among producers, grid operators, regulators, ports, and industrial clusters.

Mid-Term (2–5 years):

- ***Establish a National Hydrogen Data Center:*** Set up an independent or semi-autonomous body to collect, verify, and publish market data regularly.
- ***Develop Analytics Tools:*** Create modules for demand forecasting, cost trends, and carbon intensity tracking.
- ***Publish Regular Market Reports:*** Release quarterly market briefs to inform policymakers, financiers, and industry players
- ***Enable Application Programming Interfaces (API) Integration:*** Build real-time links with international databases and private digital platforms time data feeds.

Long-Term (5+ years):

- ***Advanced Forecasting & AI:*** Deploy AI tools to predict production costs, offtake trends, and grid integration needs.
- ***Foster International Data Linkages:*** Harmonize India's hydrogen market data standards with global hydrogen trade hubs to enable cross-border transparency and benchmarking.
- ***Pilot Hydrogen Exchange:*** Begin with bilateral contracts and auctions for green hydrogen and derivatives (like green ammonia).

- ***Sustain Stakeholder Engagement:*** Keep industry, research, and government stakeholders aligned through feedback loops and periodic updates.

Key Enablers: Clear mandates for data disclosure, strong privacy frameworks, digital infrastructure, and cross-stakeholder collaboration will ensure that India's green hydrogen ambitions stand on a strong, transparent market foundation.

Strategic Spatial and Capacity Expansion Roadmap

India's National Green Hydrogen Mission targets 5 million metric tonnes (MMT) of annual production by 2030. Its success depends on a smart, phased approach that leverages strategic hubs and port infrastructure to realize scale and cost competitiveness.

Short-Term (0–2 years): Phase 1-Building Early Hubs and Pilot Projects

Production target: 0.5-1 MMT H_2/annum: The first phase focuses on establishing green hydrogen hubs near industrial clusters such as refineries, fertilizers, steel, and mobility sectors. By co-locating electrolysers with renewable energy sources, these hubs minimize transmission losses and costs. Ports play a vital role too facilitating exports of derivatives like green ammonia and enabling early imports of electrolyser and its components.

Mid-Term (2–5 years): Phase 2-Demonstration and De-Risking

Production target: 2-3 MMT H_2/annum: Early pilot projects, supported under the SIGHT programme, will receive viability gap funding and capital subsidies. These pilots will validate business models, demonstrate supply chain viability, and create bankable templates for larger rollouts. Lessons learned will guide grid integration, water management, and cost-effective offtake agreements.

To truly unleash the potential of green hydrogen and achieve cost competitiveness, we need to shift our focus. Here's what I believe is essential:

- Implement higher carbon pricing for fossil-based hydrogen.
- Mandate green hydrogen adoption across key industrial sectors.
- Drive policy reforms to create demand and reduce risk for investors.

Long-Term (5+ years): Phase 3-Scaling Up with Competitive Bidding

Production target: 4-5 MMT H_2/annum: By 2029–30, India will move into large-scale deployment. Investment cycles will align with mature demand and growing domestic supply chains. Competitive bidding for hydrogen supply contracts will drive price discovery and efficiency, attract global players and lower the levelized cost of hydrogen.

To achieve its 5 MMT green hydrogen target by 2030, India will have to adopt a phased strategy. Phase 1 runs pilot projects and builds early hubs near industrial clusters, co-located with renewables and ports for efficient supply chains and exports. Phase 2 scales pilot projects with SIGHT funding to validate technologies and business models, while policy reforms, carbon pricing, and sectoral mandates for green hydrogen usage in various sectors like refineries, fertilizers, steel, and mobility sectors create demand and reduce investment risks. Phase 3 focuses on large-scale deployment through competitive bidding, robust domestic manufacturing, and strengthened export infrastructure, ensuring cost competitiveness and global market access. This roadmap aligns industry, policy, and finance to transform India into a green hydrogen leader.

Integrated Demand and Value Chain Development Trajectory

Beyond financial incentives, the National Green Hydrogen Mission's phased approach should outline a time-bound pathway to secure domestic demand and strengthen energy security. A key strategy is enforcing sector-specific blending quotas and minimum consumption mandates in priority industries like petroleum refining, fertilizers, and steel. By mandating blending ratios, these sectors will gradually shift from grey hydrogen, creating stable demand that supports large-scale production.

In the short term (0–2 years), clear targets should be notified and pilot projects launched to test blending in refineries and fertilizer units. Regulatory monitoring and compliance systems will ensure obligations are met. Simultaneously, Production Linked Incentive (PLI) schemes, import duty rationalizations and R&D support should promote and strengthen local supply chains for balance-of-plant components; power electronics, compression, storage, and distribution equipment.

In the mid-term (3–5 years), blending ratios should be increased and expanded to sectors like steel and transport. Infrastructure for dedicated pipelines and industrial clusters must be developed to handle growing volumes. Local manufacturing of balance-of-plant equipment should be scaled up through partnerships.

In the long term (6–10 years), blending mandates will tighten further, and the entire green hydrogen value chain must be developed to foster economic self-reliance. This integrated approach will cut emissions, secure energy needs, and position India as a competitive global green hydrogen hub aligned with its net-zero vision.

Global Export Strategy and International Partnership

India's National Green Hydrogen Mission sets a clear and time-bound roadmap for transforming the country into a global hub for green hydrogen exports by 2030, aiming to capture at least 10% of the global market. This ambition builds on three pillars: cost leadership, dedicated export infrastructure, and robust international partnerships, each with actionable milestones.

In the short term, by 2026-27, there should be a plan to scale up low-cost production by accelerating giga-scale renewable energy parks and boost green hydrogen production under the Production Linked Incentive (PLI) scheme. Simultaneously, early pilot green hydrogen hubs to be developed along coastal regions rich in solar and wind resources. Strategic MOUs with major green hydrogen, ammonia importing nations states will help secure long-term demand.

By 2028-29, the focus should shift to building world-class export infrastructure; dedicated pipelines, liquefaction terminals, and hydrogen-ready ports to handle large-scale shipments. Partnerships for establishing green shipping corridors and bunkering facilities will be critical to reach distant markets efficiently.

Looking towards 2030, India aims to consolidate its position as a cost leader through continued innovation and economies of scale, while deepening international collaborations into long-term supply contracts and joint ventures.

With this phased, actionable plan, India is poised to not only meet its domestic decarbonisation goals but also emerge as a reliable, affordable, and sustainable supplier of green hydrogen, powering global clean energy transitions.

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