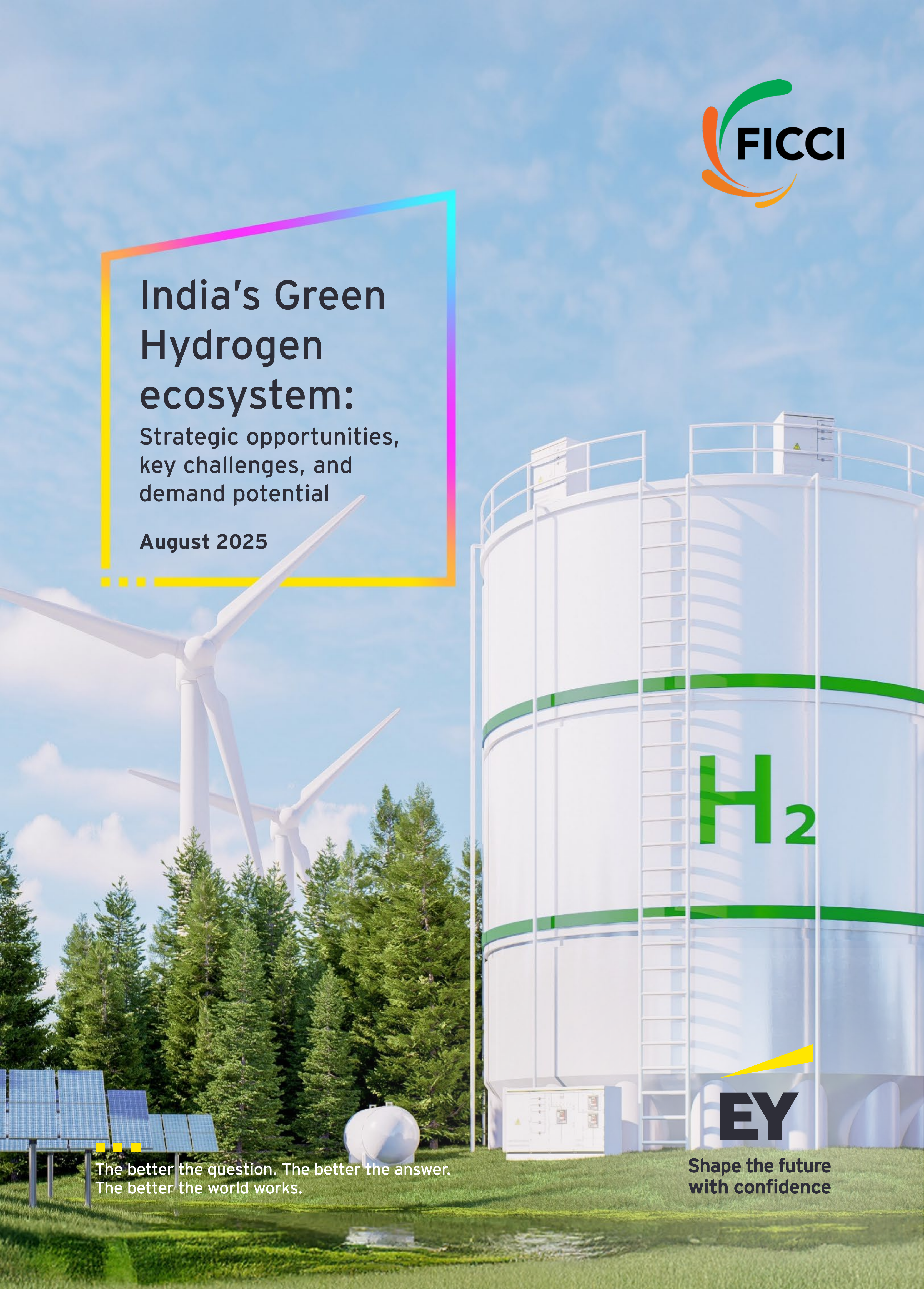

FICCI

India's Green Hydrogen ecosystem:

Strategic opportunities, key challenges, and demand potential

August 2025

The better the question. The better the answer.
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EY
Shape the future
with confidence

Acknowledgement

FICCI extends its sincere gratitude to all stakeholders who contributed to the development of this report. Special thanks to the FICCI Green Hydrogen Committee Chair, Co-Chair and members for conceptualizing the report and guiding the team throughout its development with their input and suggestions.

FICCI also acknowledges the efforts of Ernst & Young LLP for leading the research and drafting the report in consultation with the industry and other stakeholders in this sector. The EY team conducted a detailed and comprehensive study to develop a holistic perspective on the potential opportunities and pathways for Green Hydrogen adoption in the country.

The report underscores the pivotal role of demand-side enablers, especially from industries like refining, steel, aviation and fertilizers in creating a sustainable and long-term green hydrogen market. It outlines priority use-cases, procurement models, cost dynamics, and actionable steps needed to stimulate demand.

FICCI further appreciates the valuable contributions of various organizations, associations, and individual experts who generously shared their time, perspectives, and expertise. Their inputs were instrumental in shaping the final report.

FICCI expresses its gratitude to everyone whose efforts were essential to the creation of this report.

Foreword

Jyoti Vij
Director General
FICCI

Green Hydrogen is a game changer for India's energy transition. It is indispensable for decarbonizing sectors that are otherwise difficult to abate through conventional electrification, such as steel, fertilizers, cement, refining, chemicals, and heavy-duty transport. Its derivatives, such as green ammonia and methanol, can decarbonize international shipping and expand India's role in global trade.

India's unique advantage in its abundant solar and wind resources positions it to become one of the most cost-competitive producers of Green Hydrogen globally. Green Hydrogen is not just about clean energy, it is about economic opportunity, and global leadership in a new industrial age.

We are delighted to share that FICCI and EY have jointly developed the report titled "India's Green Hydrogen ecosystem: Strategic opportunities, key challenges, and demand potential", suggesting ways to advance Green Hydrogen offtake among industrial sectors and highlighting the sectoral opportunities, industrial demand, and multi-pronged regulatory and industrial approach needed for increasing Green Hydrogen adoption in the country.

The report underscores Green Hydrogen's strategic potential, not only as a decarbonization tool but also as a catalyst for industrial competitiveness, job creation, and export-driven growth. It also proposes necessary policy recommendations and industrial measures to create a conducive green hydrogen production ecosystem in the country as well as to increase its adoption among industries.

We so hope that you will find the report useful.

Somesh Kumar
Partner & Leader,
Power & Utilities, EY India

Green Hydrogen represents a pivotal opportunity for India's energy transition, bridging the gap between climate ambition and industrial competitiveness. I am pleased to present this joint report by FICCI and EY titled "India's Green Hydrogen ecosystem: Strategic opportunities, key challenges, and demand potential". Drawing on sectoral insights of EY and FICCI's platform leadership, the report provides a comprehensive snapshot of India's current landscape, detailing emerging demand prospects, technology readiness, policy dynamics, and investment pathways.

India has made significant strides in building its renewable energy base, but scaling up to support 5 MMT per year of Green Hydrogen by 2030 will require additional 125 GW of dedicated renewable capacity, alongside robust water logistics and domestic electrolyzer manufacturing capabilities. As this report outlines, early-stage Green Hydrogen projects face elevated cost structures, typically around double the cost of Grey Hydrogen, driven by transmission, efficiency, and capex gaps. Addressing these barriers calls for an integrated strategy: supportive fiscal and open-access regimes, demand aggregation mechanisms such as purchase obligations, and export-linked trade corridors.

I commend FICCI for their leadership in convening this report and their continued advocacy for multi-stakeholder engagement. It is our hope that these findings will inform policy deliberations, strategic planning, and partnerships, ultimately enabling India to emerge as a global hub for clean hydrogen.

Sandeep Narang

Partner

Strategy & Transactions, EY India

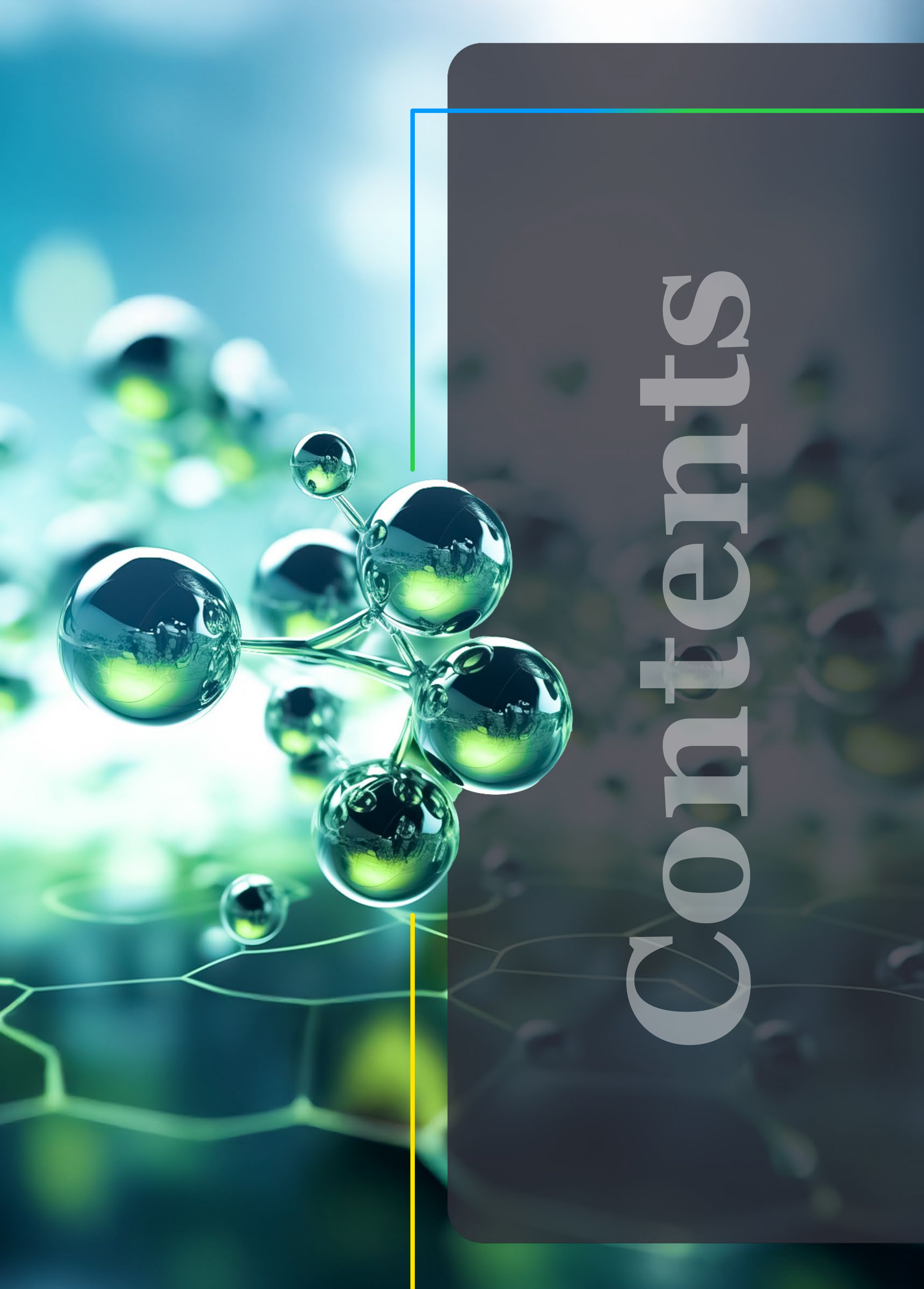
It is with great pride that we present this report, "India's Green Hydrogen ecosystem: Strategic opportunities, key challenges, and demand potential", jointly developed by EY and the Federation of Indian Chambers of Commerce and Industry (FICCI).

Green Hydrogen and its derivatives hold immense promise for enabling deep decarbonization across hard-to-abate sectors and enhancing energy security. This will position India as a global leader in the clean energy economy as a major supplier of molecules produced using green energy. Scaling up Green Hydrogen production comes with its own complexity of challenges, ranging from technology costs and infrastructure readiness to policy alignment and market creation.

This report takes a comprehensive view of the current landscape, exploring opportunities in different sectors, identifying key challenges and barriers and assessing India's Green Hydrogen demand potential. It also outlines actionable recommendations to accelerate Green Hydrogen adoption and enhance offtake across industries. Our views draw on extensive research, market insights, and stakeholder consultations, aiming to provide a practical roadmap for industry, policymakers and investors.

I hope this report serves as a valuable resource in guiding strategic decision-making, fostering innovation, and unlocking the full potential of India's Green Hydrogen ecosystem.

I would like to thank FICCI for their partnership in this initiative, and the many stakeholders who contributed their perspectives. Together, we can turn India's Green Hydrogen vision into a transformative reality.



Contents

The information presented in this report has been collated from a range of credible sources, including government bodies, industry reports, media outlets, and international organizations. For further details, please refer to the References section.

Executive summary

India is uniquely positioned to become a global leader in the production, utilization, and export of Green Hydrogen, leveraging its abundant renewable energy resources, policy momentum, and rapidly growing domestic demand. The National Green Hydrogen Mission (NGHM), launched in January 2023 with an outlay of INR19,744 crore (US$2.4 billion), aims to establish an annual Green Hydrogen production capacity of 5 million metric tons (MMT) by 2030. This initiative is expected to mobilize investments exceeding INR8 lakh crore (US$91.95 billion), create half a million jobs, and reduce fossil fuel imports by INR1 lakh crore (US$11.49 billion) annually, while abating 50 MMT of CO_2 emissions.

India's strategic advantages include some of the lowest renewable electricity costs globally, high solar irradiance, and a robust transmission infrastructure. These factors are expected to drive down the levelized cost of Green Hydrogen to INR260-310/kg (US$3–3.7/kg) by 2030. With the global hydrogen market projected to grow from US$8.8 billion in 2024 to US$199 billion by 2034, India is targeting significant export opportunities, especially to the EU, Japan, and South Korea.

Key sectors identified for Green Hydrogen deployment include steel, fertilizers, refineries, transportation, and energy storage. Notably, the steel sector could drive demand up to 30 MMT by 2050, while refinery and fertilizer sectors are actively exploring substitution of Grey Hydrogen with green alternatives. Pilot projects under NGHM are already underway in steel, mobility, and maritime sectors, complemented by incentives for electrolyzer manufacturing and Green Hydrogen production through the Strategic Interventions for Green Hydrogen Transition (SIGHT) program.

Despite these opportunities, several challenges remain. These include high capital costs, limited infrastructure for storage and transportation, technology dependencies for critical electrolyzer components, water resource constraints in renewable-rich regions, and the absence of harmonized international standards. Moreover, cost competitiveness against grey hydrogen remains a barrier, requiring further reduction in renewable electricity and electrolyzer costs.

To support this transition, India has adopted a robust multi-level policy framework. At the central level, the NGHM supports production incentives, R&D, human resource development, and regulatory standardization. Several states such as Uttar Pradesh, Maharashtra, Rajasthan, and Andhra Pradesh have also introduced policies providing capital subsidies, tax incentives, and priority land allotment to attract investments in Green Hydrogen.

Realizing the full potential of Green Hydrogen in India will require sustained momentum through coherent policy implementation, accelerated infrastructure deployment, stronger international collaboration, and deeper private sector engagement. With coordinated efforts across central and state governments, industry, and research institutions, India can significantly advance its energy transition, enhance energy security, and emerge as a key player in the global Green Hydrogen economy.


1

The Green Hydrogen opportunity landscape

Strategic advantages and market potential

India possesses several strategic advantages that position it favorably in the global Green Hydrogen market. The country has achieved one of the world's most competitive renewable energy costs, with solar and wind power becoming increasingly affordable. India's geographical location near the equator ensures ample sunlight throughout the year, with solar irradiance of 4-7 kWh/m²/day and 2,300-3,200 sunshine hours annually.

The global Green Hydrogen market, valued at US$8.78 billion in 2024, is projected to reach US$199.22 billion by 2034, growing at a CAGR of 41.46%. India's Green Hydrogen market specifically is expected to reach US$2,812.8 million by 2030, representing a remarkable 56% CAGR from 2024 to 2030.

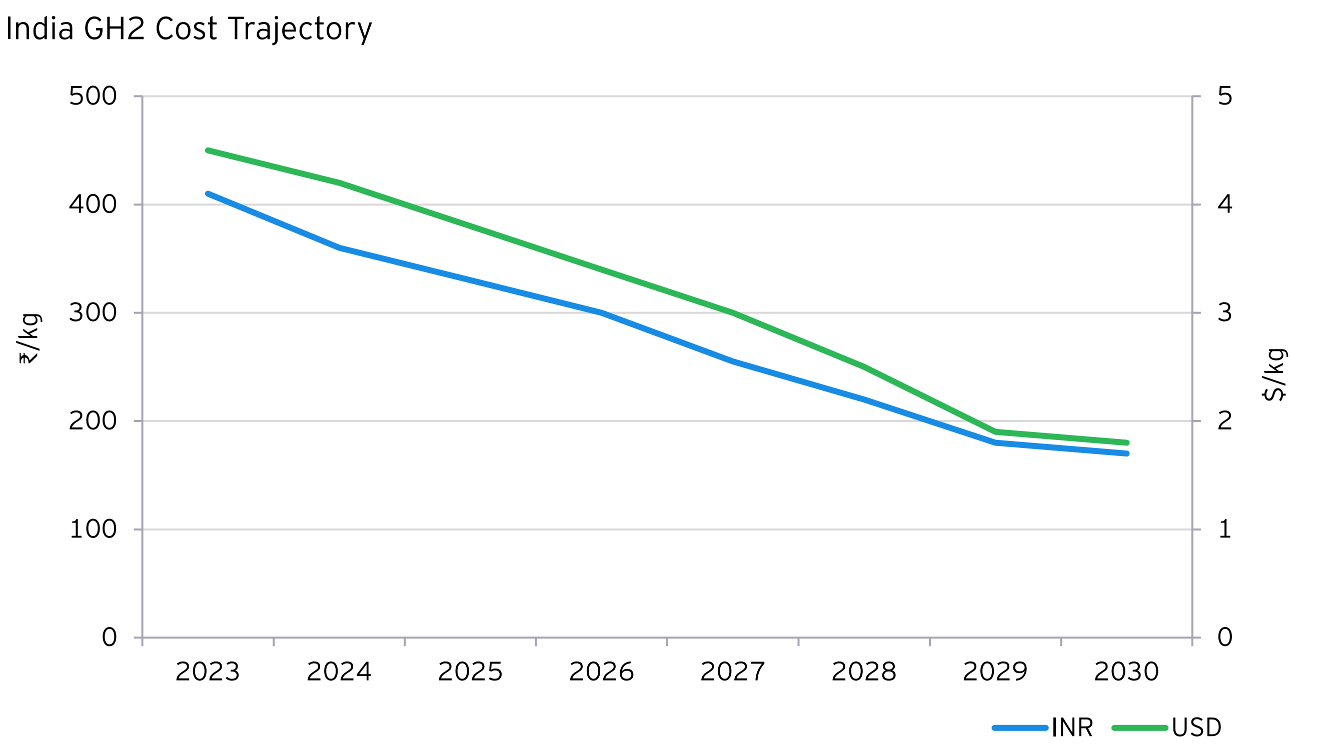
Cost reduction trajectory

One of the most promising developments is the projected cost reduction for Green Hydrogen production in India. Current production costs of US$4-4.5 per kg are expected to decline significantly due to government support and technological improvements.

The levelized cost of Green Hydrogen is projected to fall to INR260-310 per kg (US$3-3.75 per kg) by 2030, representing up to 40% cost reduction from current levels. This reduction is attributed to:

- Cheap renewable electricity provided to manufacturers
- Waiver of Inter-State Transmission Charges for open access
- Reduced GST rate of 5% for hydrogen
- Electrolyzer manufacturing cost reductions of 7-10% over five years.

Figure 1 - Projected cost reduction of Green Hydrogen in India from 2023 to 2030



Source - EY analysis

Export potential and global market access

Under the National Green Hydrogen Mission, India is advancing towards its 2030 target of 5 million tons of Green Hydrogen production, supported by significant policy and financial backing, including certification schemes and domestic electrolyzer manufacturing. The government has prioritized port-based hydrogen hubs and is fostering international collaborations to build a robust hydrogen ecosystem. Recent efforts include joint ventures, technology sharing, infrastructure development, and offtake agreements to enable large-scale Green Hydrogen and ammonia production, export, and bunkering.

The country could potentially capture 10% of the global market, exporting approximately 10 MMT of Green Hydrogen/Green Ammonia per annum. European Union, Japan, and South Korea represent key import markets, with the EU's REPowerEU plan targeting 20 million tons of Green Hydrogen consumption by 2030.

Alvarez & Marsal projects that India could achieve US$3-5 billion in Green Hydrogen exports and US$7-15 billion in import substitution within the next decade. This positions India to become a major player in the emerging global hydrogen economy.

Key industrial applications and sectoral opportunities

Steel industry transformation

The **steel sector** presents one of the most significant opportunities for Green Hydrogen adoption. Currently responsible for 8% of global CO2 emissions, the steel industry can achieve dramatic emission reductions through Hydrogen Direct Reduction (H-DRI) technology. The National Green Hydrogen Mission supports pilot projects in steel manufacturing, focusing on 100% hydrogen use in DRI processes and gradual substitution of fossil fuels.

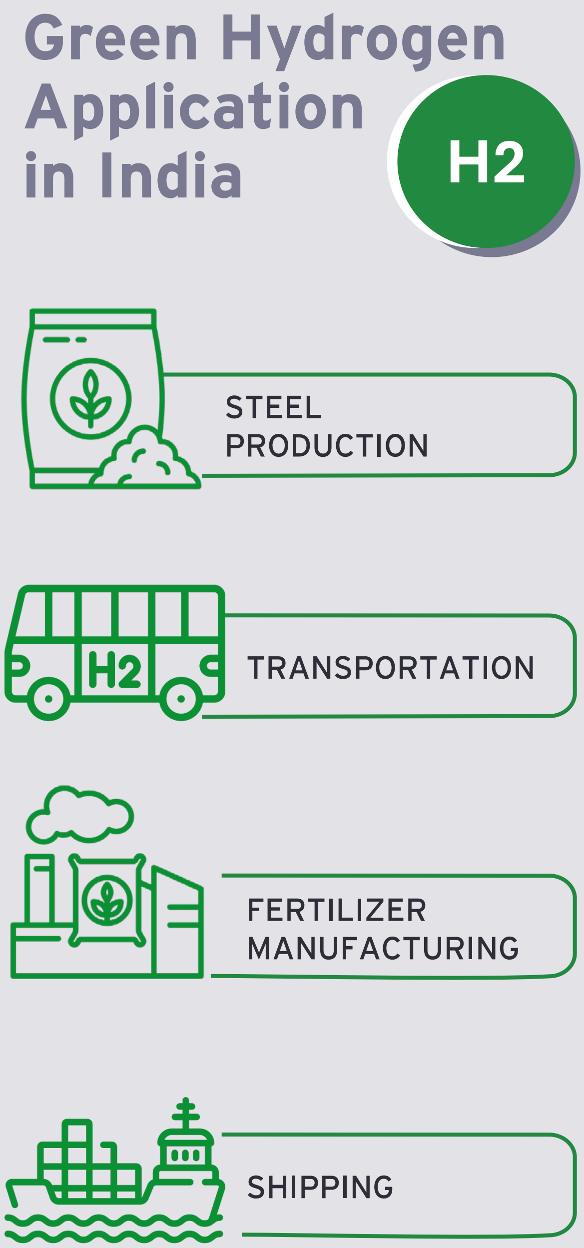
Fertilizer and chemical industries

The **fertilizer industry**, which currently relies heavily on imported natural gas and ammonia, represents another major opportunity. Green Hydrogen can enable ammonia synthesis for fertilizer manufacturing, supporting India's net-zero vision while reducing import dependency. This transition could significantly insulate the country from global price volatility in fertilizers and natural gas.

Transportation and mobility

India has initiated **five pilot projects** under the National Green Hydrogen Mission for transportation, deploying 37 hydrogen-powered vehicles (15 fuel cell-based and 22 hydrogen internal combustion engine-based) across 10 routes. The government allocated Rs. 208 crore (US$25.06 million) for these pilot projects, which include nine hydrogen refueling stations and are expected to be operational within 18-24 months.

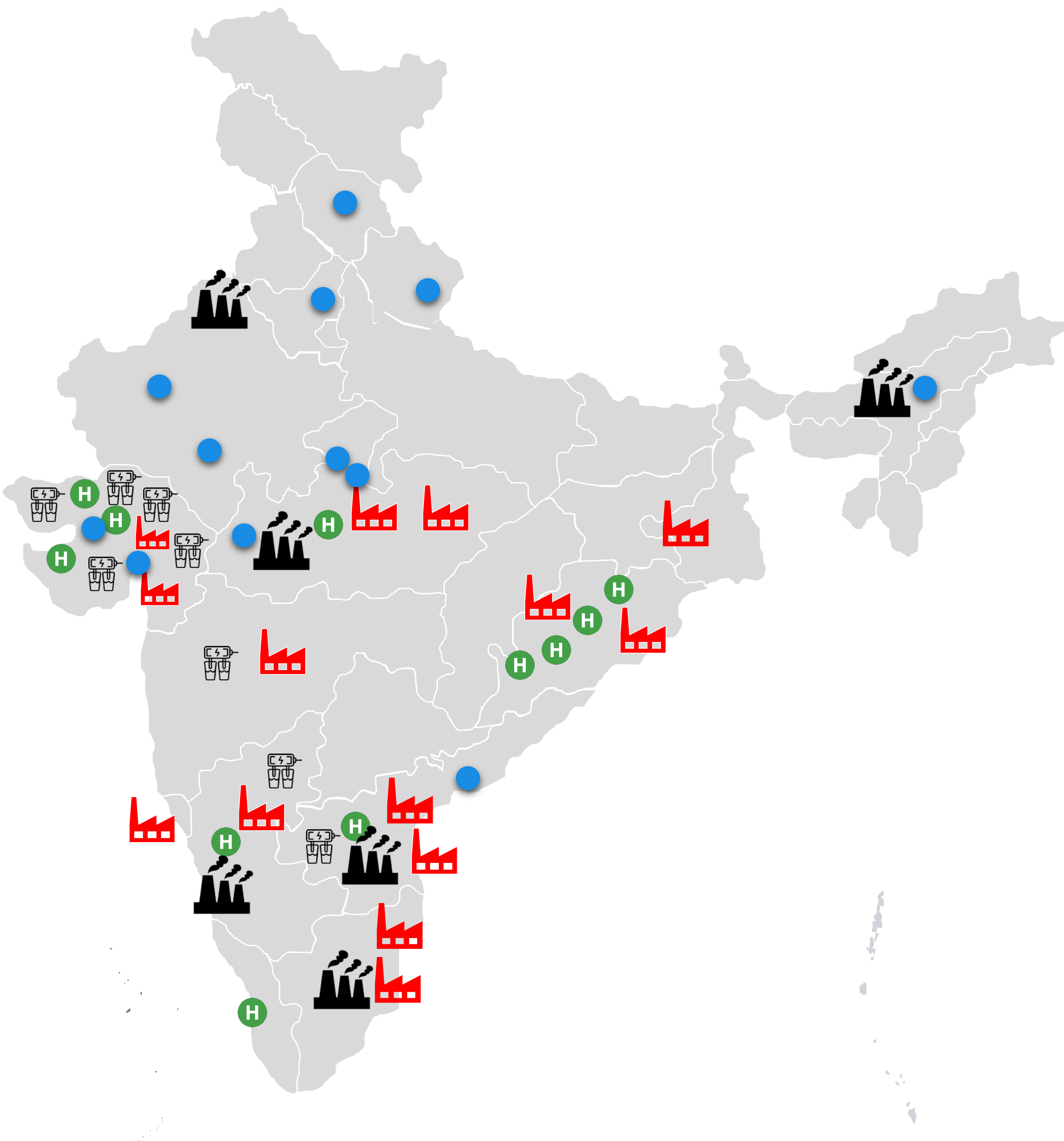
Figure 3: Green Hydrogen applications across key industrial sectors in India



Existing projects in different sectors

India is rapidly advancing in the Green Hydrogen sector, reinforcing its broader commitment to clean energy and climate action. Under the National Green Hydrogen Mission, the country envisions establishing itself as a global hub for the production, utilization, and export of Green Hydrogen. Supported by government incentives (Central and state) and strategic public-private collaborations, a growing number of GH2 production projects are being implemented across various states. Simultaneously, India is scaling up its electrolyzer manufacturing capacity which is an essential element for the widespread adoption of hydrogen technologies. Key industrial sectors, including fertilizers and refineries, are increasingly incorporating Green Hydrogen into their operations, fostering a strong and evolving demand landscape. These initiatives reflect India's strategic focus on decarbonization, energy self-reliance, and leadership in the global hydrogen economy. The accompanying map provides a visual representation of the geographical distribution of Green Hydrogen and green ammonia-related projects, highlighting clusters of activity where government incentives are being leveraged. In addition, several Green Hydrogen projects have already been commissioned and are currently operational, marking tangible progress in the sector.

Figure 2: Green Hydrogen projects in India



Source - EY analysis

2

Major challenges and barriers

Infrastructure and storage challenges

A primary challenge constraining the large-scale deployment of Green Hydrogen is its comparatively high production cost relative to conventional hydrogen sources. Currently, hydrogen derived from fossil fuels, such as Black and Grey Hydrogen is available at a significantly lower cost, typically ranging between INR150 and INR220/kg (US$1.8-2.6/kg). In contrast, Green Hydrogen production remains substantially more expensive, with current estimates falling between INR350 and INR500/kg (US$4.1-5.9/kg).

This price differential is further compounded by the additional costs required to condition hydrogen for end-use. Processes such as compression, liquefaction, and conversion to ammonia introduce considerable incremental expenses. For instance, liquefaction alone can increase the cost by approximately INR150 to INR250/kg (US$1.8-2.6/kg).

Moreover, the development of dedicated infrastructure for hydrogen transport and storage presents a significant financial burden. The capital cost of constructing hydrogen pipelines is estimated to be 110% to 150% higher than that of natural gas pipelines. Storage technologies, especially those employing advanced, material-based solutions, also add substantially to overall system costs, with some options reaching up to INR3,500/kg (US$41.2/kg)

Water requirements and availability

Although the total water requirement for Green Hydrogen production is modest compared to that of the agricultural sector, a critical barrier lies in the geographical mismatch between renewable energy availability and water resources. High-potential regions for solar and wind energy generation such as Rajasthan, Gujarat, and Tamil Nadu also face persistent water scarcity. The development of large-scale Green Hydrogen facilities in these regions may further strain already limited local water resources.

This challenge is further intensified by several interrelated factors:

Geographical misalignment

To maximize efficiency and reduce transmission losses, Green Hydrogen production facilities are typically co-located with renewable energy sources. However, many of these renewable-rich regions are also water-stressed, presenting a structural conflict between energy development and water resource availability.

Stringent water purity requirements

Electrolyzers require ultra-pure, demineralized water to ensure optimal functionality and equipment longevity. The treatment process to achieve this level of purity is both energy-intensive and costly. The use of untreated or even conventionally treated water can result in reduced efficiency and accelerated degradation of equipment, increasing both operational and maintenance costs.

Land use trade-offs

While the footprint of electrolysis units is relatively small, the associated renewable energy infrastructure—particularly solar PV and wind farms—requires substantial land area. In regions with limited arable land, this can lead to direct competition with agriculture and other critical land uses. This dynamic not only complicates land allocation decisions but also adds another layer of complexity to water resource planning, especially where land and water demands intersect.

Technology and manufacturing dependencies

India's ambition to become a global leader in Green Hydrogen is closely tied to its ability to scale up domestic electrolyzer manufacturing. While it is estimated that approximately 80%–82% of electrolyzer components can be indigenized with current capabilities, the country remains significantly dependent on the import of critical raw materials. These include essential minerals such as platinum, iridium, nickel, molybdenum, and zirconium, which are vital for the manufacturing of high-efficiency electrolyzers, particularly Proton Exchange Membrane (PEM) and Solid Oxide Electrolyzers (SOE). The absence of these minerals in India's domestic reserves poses a strategic challenge, creating supply chain vulnerabilities, increasing cost pressures, and exposing the sector to geopolitical risks and global price fluctuations.

To effectively address these challenges, India must transition its focus from merely scaling production to establishing a resilient and self-sustaining electrolyzer manufacturing ecosystem. This requires a comprehensive strategy that prioritizes domestic innovation through targeted investments in research and development, expands local manufacturing capacities, and implements supportive policy frameworks designed to attract both domestic and foreign investment. Equally important is the need to strengthen India's integration into global critical mineral value chains through strategic bilateral sourcing agreements and international partnerships.

Financial and investment challenges

High capital expenditure represents a major barrier to widespread adoption. Green Hydrogen projects require substantial upfront investments in production facilities, storage infrastructure, and transportation networks. Indian banks face constraints in financing long-gestation projects, with most able to provide funding for only 5-7 years compared to the longer-term needs of hydrogen infrastructure. The cost of Green Hydrogen remains significantly higher than Grey Hydrogen, US$1.8/kg for Grey vs. US$4.1/kg for Green), making economic viability challenging without policy support and incentives.

Many Green Hydrogen projects in India are still in the pilot or planning stages and rely significantly on government support to be viable. Without a long-term and stable investment framework such as green bonds, viability gap funding, and structured public-private partnerships, the projects may struggle to scale commercially. To encourage ongoing private sector investment, India needs to adopt effective risk management strategies for early-stage projects, and create a robust ecosystem that fosters infrastructure development, boosts demand, and provides reliable and sustainable revenue models.

Market challenges

Despite increasing national commitments toward decarbonization, the Green Hydrogen industry faces significant market-related obstacles that hinder its broad adoption. A primary issue is the currently limited market demand for Green Hydrogen alongside a lack of cohesive and supportive policy frameworks. In numerous regions, government incentives and subsidies predominantly favor blue hydrogen—produced from natural gas with carbon capture and storage (CCS), over Green Hydrogen. Although blue hydrogen generates fewer emissions than conventional grey hydrogen, it remains more economically attractive due to substantially lower production and infrastructure costs.

Consequently, major industrial consumers such as steel manufacturing, refining, and ammonia production, which are key hydrogen demand sectors, continue relying largely on fossil fuel-based hydrogen driven by cost considerations. The absence of robust market incentives, mandates, or regulatory mechanisms to encourage a transition to Green Hydrogen delays its penetration into these high-emission industries.

The hydrogen market currently lacks the maturity seen in other energy sectors like oil, natural gas, and electricity. It is characterized by limited liquidity and insufficient market transparency. Most hydrogen sales occur through bilateral contracts, and there is a notable absence of public trading platforms or spot markets. This limited market visibility and inadequate price discovery mechanisms undermine investor confidence and restrict capital inflows necessary for scaling Green Hydrogen projects.

Regulatory challenges and global fragmentation

The absence of a harmonized global regulatory framework significantly hampers international collaboration and trade in hydrogen technologies. Key regulatory dimensions including production methods, emissions accounting, purity standards, and safety protocols vary widely across jurisdictions. Without standardized definitions, particularly regarding what constitutes "clean" or "green" hydrogen, regulatory fragmentation risks rise, leading to inconsistent certification processes and uneven competitive conditions. These disparities complicate cross-border trade, elevate compliance burdens, and inhibit technology dissemination.

Additionally, hydrogen's unique physical and chemical properties necessitate stringent regulatory oversight. Its flammability, low volumetric energy density, and propensity to cause material embrittlement in pipelines and storage facilities present distinct safety and engineering challenges. While standardization initiatives such as those led by ISO Technical Committee 197 are underway, comprehensive and universally adopted safety and handling standards remain incomplete. Establishing such standards is crucial for ensuring the safe production, transport, storage, and utilization of hydrogen especially as it becomes integrated into urban and industrial infrastructures.

Public acceptance and safety considerations

The long-term success of the hydrogen economy depends on more than just overcoming regulatory and market hurdles; it fundamentally hinges on earning public trust and social acceptance. Given hydrogen's characteristics, being odorless, colorless, highly flammable, and prone to leakage due to its small molecular size, communities often harbor safety concerns. Additionally, hydrogen's lower volumetric energy density compared to conventional fuels requires larger storage volumes or elevated pressures, complicating infrastructure design and safety management.

Public resistance can result in delays in project approvals, disrupt supply chain development, and stall the deployment of critical infrastructure such as hydrogen hubs, refueling stations, and pipeline networks. To address these concerns effectively, transparent communication, proactive public engagement, and demonstrable safety measures are indispensable.

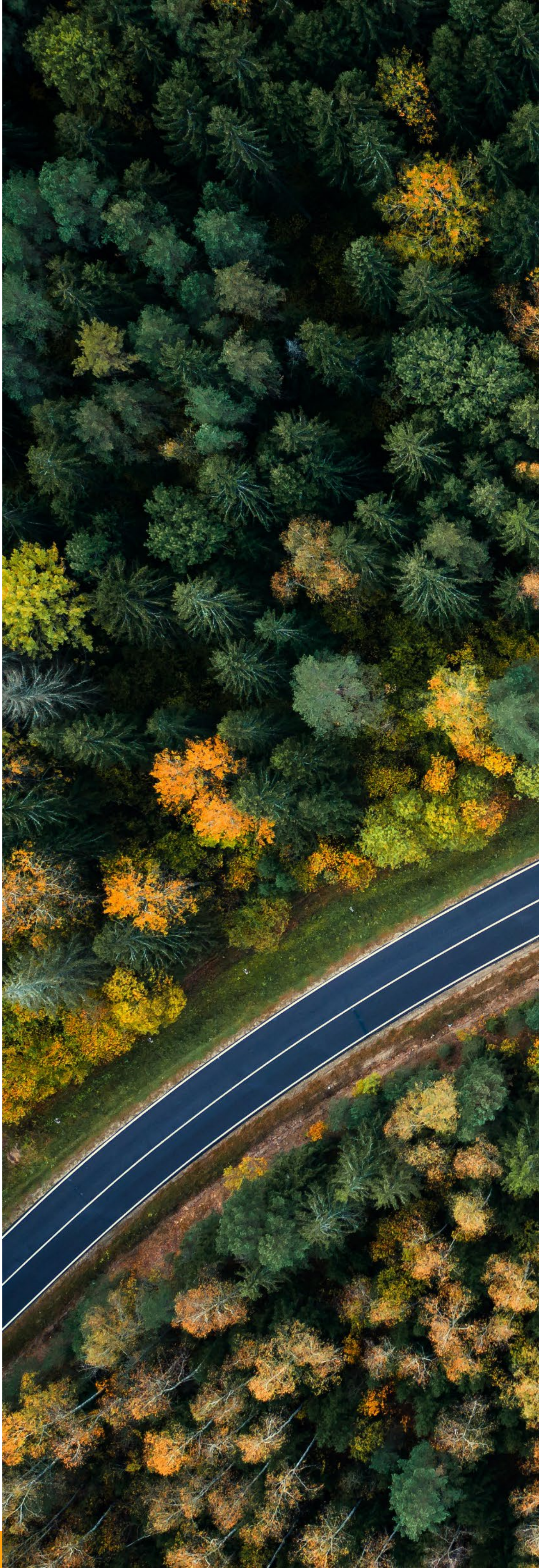
Governments, regulators, and industry stakeholders must collaborate to establish and enforce rigorous safety standards while engaging in continuous community outreach. Showcasing successful implementation examples, facilitating stakeholder consultations, and maintaining transparent safety records will be vital to building public confidence. Public acceptance is not simply an ancillary factor but a fundamental prerequisite for advancing hydrogen infrastructure from pilot demonstrations to a fully integrated component of energy systems at national and international scales.

Port-related infrastructure and logistical constrain

The large-scale development of Green Hydrogen is confronted with substantial challenges related to port infrastructure and logistics that must be resolved to facilitate efficient production, storage, and international transportation. Many existing port facilities are not equipped with the specialized infrastructure necessary for handling hydrogen and its derivatives, such as liquefied hydrogen or ammonia. This includes the need for cryogenic storage, high-pressure systems, and dedicated loading and unloading terminals. Logistical hurdles also include insufficient intermodal connectivity, such as hydrogen-compatible rail and pipeline systems, along with the absence of harmonized international regulations and safety standards. The GH2/GA developers have raised an issue of unreasonably high port charges at Gopalpur Port, Odisha compared to other ports in India. This will negatively affect the feasibility of the project and significantly increase the cost of green ammonia, which is already more expensive than grey ammonia. As a result, such projects are likely to become commercially unviable for export markets.

Environmental issues

Green Hydrogen and green ammonia initiatives in India are regulated under Environmental Clearance (EC) requirements established by the Ministry of Environment, Forest and Climate Change (MoEFCC). The necessity for clearance is determined by various factors, including project scale, location, feedstock, and related infrastructure such as pipelines, ports, and storage facilities. In July 2023, the MoEFCC granted an exemption from EC requirements specifically for standalone Green Hydrogen and green ammonia plants. Several states have proactively implemented policies to support these exemptions within designated renewable energy zones to promote project development. However, project developers are still required to obtain environmental consents from State Pollution Control Boards in compliance with existing air and water pollution regulations. Furthermore, there is an increasing push from developers advocating for EC exemptions for additional Green Hydrogen derivatives, including e-methanol and sustainable aviation fuels (e-SAF).



Limited availability of power

Electricity is the essential and primary requirement for producing Green Hydrogen through electrolysis. Without a dependable and clean power source, sustainable production of Green Hydrogen is not feasible. The development of Green Hydrogen and ammonia projects in India encounters significant challenges due to the limited availability of consistent renewable power and delays in connectivity and transmission infrastructure. Although India is rapidly expanding its renewable energy capacity, intermittent generation and grid constraints frequently impede the reliable and cost-effective supply of electricity needed for large-scale electrolyzer operations. By 2030, there is a projected need for 60-80 GW of round-the-clock renewable energy power to support the announced and upcoming projects under the National Green Hydrogen Mission (NGHM). To ensure the timely commissioning of Green Hydrogen and ammonia projects, the transmission system must be established well in advance. However, developers have reported delays in transmission and connectivity that extend beyond 2030, which could consequently postpone the progress of these projects. It is imperative for all stakeholders, including government agencies, project developers, and utility companies, to collaborate effectively to overcome these barriers and fully harness the opportunities presented by Green Hydrogen in India's energy transition. It is essential for all stakeholders (government agencies, project developers, and utility companies) to work together effectively to overcome these challenges and fully realize the potential of Green Hydrogen in India's energy transition.

3

Government initiatives and policy framework

National Green Hydrogen Mission

India is an emerging economy that must ensure that its energy use is divergent as its demand is growing very rapidly. India is currently the fastest-growing major economy and the third-largest energy user in the world. Due to this, India's reliance on imported fossil fuels has led to a remarkable US$190 billion energy import bill in 2024 alone. This dependency brings both economic risks and climate change challenges. India has made very ambitious climate commitments and hydrogen has been discussed as a one practical answer to a few issues given its growing benefits as new segment that many countries are adopting in their energy strategies and policies. Many countries have grouped and clustered to help push this transition into hydrogen into their economies. However, there are technological, economical and policy obstacles before hydrogen becomes an adequately cost-effective way to decrease greenhouse gas (GHG) emissions. Hydrogen must be produced, distributed and utilized at competitive cost and efficacies to reach its full potential.

In this regard, India has also introduced their commitment for hydrogen usage in the country in various segments from production to utilization of hydrogen. The Ministry of New and Renewable Energy (MNRE), an important arm of Government of India, introduced National Green Hydrogen Mission, with an objective to make India a global hub of production, usage and export of Green Hydrogen and its derivatives in January 2023, with budget of INR19,744 crore (US$2.4 billion). The Mission could make India a global leader in this segment. NGHM has the following objective to be achieved by 2030:

Green Hydrogen production: Achieve an annual production of at least 5 MMT.

Renewable Energy capacity: Develop 125 GW of renewable energy capacity dedicated to Green Hydrogen generation.

Investment: Mobilize INR8 lakh crore (US$91.95 billion) in total investment.

CO2 emission reduction: Prevent 50 MMT of CO2 emissions per year.

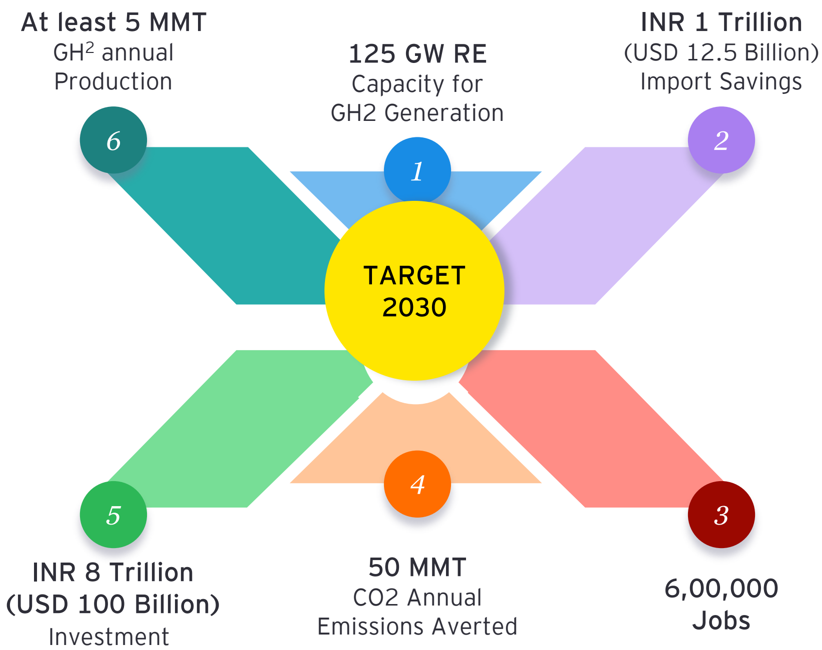
Import savings: Realize INR1 lakh crore (US$11.49 billion) in import savings.

Job creation: Generate half a million new green jobs.

NGHM has following components:

- Strategic Interventions for Green Hydrogen Transition (SIGHT) program, which includes incentives for manufacturing of electrolyzers and production of Green Hydrogen
- Pilot projects for green steel, mobility, shipping, decentralized energy applications, hydrogen production from biomass, hydrogen storage, etc.
- Development of Green Hydrogen Hubs
- Support for infrastructure development
- Establishing a robust framework of regulations and standards
- Research & Development projects
- Skill development initiatives
- Public awareness and outreach activities

Figure 3: Objectives of National Green Hydrogen Mission



The timeline below outlines the chronological progress and strategic interventions under India's National Green Hydrogen Mission from 2023 to 2030. Key schemes across sectors such as shipping, steel, R&D, and transport have been launched, alongside the phased awarding of tenders for electrolyzer manufacturing and Green Hydrogen production.

NGHM timeline

Jan 2023
- Launched National Green Hydrogen Mission

Jun 2023
- SIGHT Green Hydrogen Mode 1
- SIGHT Electrolyser Manufacturing

Aug 2023
- Launch of Green Hydrogen Standard for India

Jan 2024
- SIGHT GH2 Aggregation Mode 2A
- SIGHT Green Ammonia Aggregation Mode 2B
- Tender Awarded for Electrolyser & GH2 under Tranche I

Feb 2024

Scheme Guidelines
- Shipping Sector | Steel Sector |Transport Sector

Mar 2024

Scheme Guidelines
- 1. R &D | 2. Hydrogen Hubs | 3. Skill Development
- 4. SIGHT Green Hydrogen Mode 1 Tranche - II

Jul 2024

Scheme Guidelines
- Testing facilities, infrastructure, and institutional
- SIGHT Green Hydrogen Production- Tranche-II
- Tender floated of 4.5 Lakhs TPA GH2 production
- Tender floated for 7.39 Lakhs TPA Production and Supply of Green Ammonia

Aug 2024
- Tender awarded for Electrolyserunder Tranche-II

Sep 24
- Draft Green Hydrogen Certification Scheme of India

Oct 2024
- Tender awarded for Electrolyserunder Tranche-II

Nov 2024
- CfP for Centre of Excellence

Mar 2025
- Tender awarded GH2 Tranche II Mode I
- Approved 23 R&D Proposal
- Approved 5 Projects for testing facilities, infrastructure, and institutional support.
- Awarded 5 projects in Transport sector with 9 Hydrogen Refuelling Stations across 10 different routes
- Pilots in Steel : 2nd round of Tender awarded

Apr 2025
- Launched Green Hydrogen Certification of India (GHCI)

2026
- Shipping and ports projects
- Mobility projects
- GH2 production technologies, storage, hubs, etc.

2030

5MMTPA
- GH2 production

A substantial budget has been allocated to each of the above components highlighting the India's significant steps taken to introduce Hydrogen economy in the country. From the above components, SIGHT program plays a major role in NGHM.

Figure 4: Budget allocation under NGHM

01

INR 17,490 Cr
(USD 2.1 Billion)

SIGHT

02

INR 1066 Cr
(USD 175 Million)

Pilot Projects

03

INR 353 Cr
(USD 46 Million)

Other Components

04

INR 400 Cr
(USD 50 Million)

Hubs and other Emerging Technologies

05

INR 400 Cr
(USD 50 Million)

R&D

06

INR 35 Cr
(USD 4 Million)

Skill Development

The SIGHT program has been initiated as part of the NGHM with a substantial financial outlay of INR17,490 crore (US$2.1 billion). The program is designed to catalyze the growth of the domestic Green Hydrogen value chain through two distinct components:

Component I:

Support for electrolyzer manufacturing (US$534.94 million)

Objectives:

Maximize indigenous manufacturing capacity: The component aims to enhance the domestic production capabilities of electrolyzers, which are critical for hydrogen generation.

Lower levelized cost of hydrogen production: By increasing local manufacturing, the program seeks to reduce the overall costs associated with hydrogen production.

Ensure global competitiveness: The initiative focuses on achieving product performance and quality that meet international standards.

Increase domestic value addition: The goal is to gradually enhance the local value addition in the hydrogen production process.

Support diverse technologies: The program is open to both established and emerging technologies in electrolyzer manufacturing.

Progress to Date:

As of now, a manufacturing capacity of 3,000 MW per annum has been awarded to selected companies under this component, indicating a significant step towards achieving the program's objectives.

Component II:

Support for Green Hydrogen production (US$1,570 million)

Objectives:

Maximize production: This component is focused on increasing the production of Green Hydrogen and its derivatives within India.

Enhance cost competitiveness: The aim is to make Green Hydrogen more competitive compared to fossil-based alternatives.

Promote large-scale utilization: The initiative encourages widespread use of Green Hydrogen and its derivatives across various sectors.

Operational modes:

Mode 1: Competitive bidding based on the lowest incentive demanded over a three-year period.

Mode 2: Aggregated demand-based bidding for procurement of Green Hydrogen and its derivatives at the lowest cost.

Progress to date:

- Under Mode 1, a Green Hydrogen production capacity of 862,000 tons per annum has been allocated to various projects.
- Under Mode 2A, a live tender is currently underway for the procurement and supply of 724,000 tons per annum of green ammonia specifically for fertilizer companies.
- Under Mode 2B, 200,000 tons per annum of production capacity has been allocated for refinery use, with tenders for 22,000 TPA currently live, and results for 20,000 TPA already announced.

Pilot projects

A.

Transport sector (US$59.76 million till 2025–26)

This scheme supports the development of hydrogen-fueled transport applications, which includes:

Component A: Development and validation of hydrogen-powered buses, trucks, and four-wheelers utilizing either fuel cells or internal combustion engines.

Component B: Establishment of hydrogen refueling station infrastructure to support the growing fleet of hydrogen vehicles.

Progress to date:

Five pilot projects worth approximately US$25.06 million have been awarded, encompassing 37 hydrogen-fueled vehicles (10 buses and 27 trucks) and nine hydrogen refueling stations. Notably, Tata Motors has commenced trials of hydrogen-powered heavy-duty trucks as of March 2025.

B.

Steel sector (US$54.82 million till 2029–30)

This initiative is aimed at supporting pilot projects focused on decarbonizing the steel sector. The projects are categorized as follows:

Scheme A: Direct Reduced Iron (DRI) production using 100% hydrogen in vertical shaft furnaces.

Scheme B: Utilization of hydrogen in blast furnaces to reduce reliance on coal and coke.

Scheme C: Injection of hydrogen in vertical shaft DRI units to partially replace natural gas.

Progress to date:

Five projects have been awarded across these schemes, marking significant advancements in the steel sector's transition to greener practices.

C.

Shipping sector (US$13.86 million till 2025–26)

This scheme focuses on the development of facilities for the seaways from production of GH2 to utilization in water vessels/ ships. The support for the shipping sector is mainly categorized into two components:

Component A (US$9.64 million): Retrofitting existing vessels with Green Methanol/Ammonia or Hydrogen Fuel Cell propulsion systems. Two 12T BP AHTS offshore vessels have been selected for this initiative.

Component B (US$4.22 million): Establishment of Green Hydrogen bunkering and refueling infrastructure to facilitate the use of hydrogen in maritime applications.

Progress to date:

The VO Chidambaranar Port Authority has prepared a Detailed Project Report (DPR) for a 750 m³ Green Methanol bunkering facility.

Human Resource development (US$4.22 million till 2029-30)

This initiative aims to build a skilled workforce to support the Green Hydrogen ecosystem. Key activities include:

Continuous skill gap analysis: Regular assessments to identify skill shortages in the workforce.

Development of curricular content: Creating educational materials across various institutions to enhance knowledge in Green Hydrogen technologies.

Creation of qualification packs and training manuals: Establishing standardized training resources to ensure consistent skill development.

Promotion of private sector involvement: Encouraging private entities to participate in training and on-the-job learning opportunities.

Establishment of a certified pool of trainers: Developing a network of qualified trainers to facilitate skill development.

Progress to date:

More than 5,000 individuals have been upskilled, and Recognition of Prior Learning (RPL) training has been sanctioned for an additional 1,680 individuals, indicating a strong commitment to workforce development.

Research & Development (R&D) initiatives (US$48.19 million till 2025-26)

This scheme is designed to drive innovation in Green Hydrogen technologies with the following objectives:

Lowering costs and improving efficiency: Focused on enhancing the safety and reliability of hydrogen systems.

Building an innovation ecosystem: Fostering collaboration between academia, industry, and government to spur innovation.

Enabling commercialization: Providing policy and regulatory support to facilitate the market entry of new technologies.

Progress to date:

So far, 23 projects have been awarded under this initiative. A joint EU-India R&D initiative focused on hydrogen production from wastewater is also currently live, showcasing international collaboration in this field. MNRE has announced second call for proposals under this scheme recently to strengthen the R&D activities related to Green Hydrogen domain.

Testing facilities, standards and regulations (US$24.10 million till 2025-26)

This scheme supports the development of testing infrastructure and regulatory frameworks with the following goals:

Identifying gaps in current testing capabilities: Assessing existing testing facilities to pinpoint areas for improvement.

Creating and upgrading testing facilities: Investing in the development of state-of-the-art testing centers to support the hydrogen value chain.

Certifying technologies and processes: Establishing standards and certifications for technologies used in hydrogen production and utilization.

Ensuring safety: Promoting safety standards and encouraging participation from both public and private sectors.

Progress to date:

Three proposals have been awarded under this scheme to date, reflecting ongoing efforts to enhance testing and regulatory capabilities.

Pilot projects on innovative Green Hydrogen technologies (US$24.10 million)

This initiative funds pilot projects that focus on new and unconventional methods for producing and utilizing Green Hydrogen, particularly in decentralized applications. Key objectives include:

Exploring innovative production methods: Investigating alternative hydrogen production techniques such as floating solar, biomass, and wastewater-based production.

Demonstrating use in various applications: Validating the effectiveness of hydrogen as a fuel in residential, commercial, off-grid, and community settings.

Ensuring safety and effectiveness: Conducting rigorous testing to confirm the safety and viability of hydrogen as a fuel source in emerging sectors.

Hydrogen Valley Innovation Cluster (HVIC) and Green Hydrogen Hubs (US$24.10 million)

This scheme is a revision of previous scheme focused on setting up of Green Hydrogen Hubs in India under NGHM. The revised scheme has broader scope and HVIC has also been included as a part of the Mission. This scheme supports the development of complete GH2 value chain encompassing production, storage and transportation and has two components:

Component A

Hydrogen Valley Innovation Clusters (HVIC)

Establishment of HVICs: Hydrogen Valley Innovation Clusters (HVICs) will be strategically developed across various regions of the country to showcase the diverse applications of Green Hydrogen (GH2) across multiple sectors.

Function as test beds: These clusters will act as test beds for emerging GH2 technologies, serving as living laboratories that promote experiential learning and generate valuable insights from pilot-scale hydrogen deployments.

Fostering business innovation: HVICs are designed to drive business innovation and facilitate the creation of new business models and techno-economic solutions by establishing strategic connections between hydrogen producers and end-users (off-takers).

Land acquisition responsibilities: Each HVIC will be tasked with identifying and securing the necessary land and built-up area for its establishment at designated locations. It is important to emphasize that there is no financial provision for land acquisition under this component.

Balancing supply and demand: To ensure a balance between GH2 supply and demand, HVICs will stimulate demand through the localization and integration of the hydrogen value chain, securing commitments from end-users for GH2 applications, and implementing a comprehensive sustainability plan that extends beyond the funding period of the National Green Hydrogen Mission (NGHM).

Informing policy development: The outcomes and insights gained from HVICs will contribute to the formulation of robust policy and regulatory frameworks, which are essential for the successful implementation of other NGHM components, including the Hydrogen Hubs aimed at accelerating the national GH2 ecosystem.

Compliance with standards: GH2 production within HVICs will strictly adhere to the standards and protocols established by the Government of India.

Component B

Green Hydrogen Hubs

Definition of Green Hydrogen Hubs: A Green Hydrogen Hub is defined as a designated geographic area that encompasses a connected ecosystem consisting of hydrogen producers, end-users (both domestic and export-oriented), and the necessary infrastructure for hydrogen storage, processing, and transportation.

Strategic location: These hubs may be situated either inland or near ports to facilitate both domestic consumption and exports of GH2 and its derivatives. Ideal locations include regions with clusters of refineries, fertilizer plants, and other industries that are intensive in GH2 usage.

Production capacity requirements: Each Hydrogen Hub must have a planned or announced production capacity of at least 100,000 metric tons per annum (MTPA). Proposals demonstrating higher production capacities will be prioritized.

Encouragement of existing infrastructure: The utilization of existing infrastructure for hydrogen production, storage, transportation, and end-use applications will be actively promoted to ensure cost efficiency and scalability.

Mapping on PM Gati Shakti Portal: All infrastructure, projects, and key resources associated with the hydrogen hubs will be systematically mapped on the PM Gati Shakti portal to facilitate coordinated and optimized development.

Table 1: Summary of the NGHM achievements

Sector	Allocation (US$ million)	Status
Electrolyzer Mfg.	535	3,000 MW/year awarded
GH2 production	1,570	862 KTPA awarded under Mode 1; 724 KTPA GA tender ongoing under Mode 2A; 20 KTPA GH2 awarded under Mode 2B
Transport	60	37 vehicles; 9 stations; 5 pilots
Steel	55	5 pilots across 3 schemes awarded
Shipping	14	2 vessels retrofit; bunkering facility by 2026
HR development	4	5,000+ upskilled; 1,680 RPL trainees
R&D	48	23 projects; CoEs in review; EU–India partnership
Testing and Standards	24	3 testing proposals awarded
Innovation pilots	24	Floating solar, biomass, and off-grid GH2 use underway

State-level initiatives

In line with India's ambitious National Green Hydrogen Mission (NGHM), several states are taking a proactive role in developing their own policies and initiatives to promote the production and use of Green Hydrogen. These state-level efforts are vital for complementing the national mission and positioning India as a global leader in the Green Hydrogen economy. The key state-level initiatives and policies for Green Hydrogen in India include:

Uttar Pradesh Green Hydrogen Policy, 2024

Objectives and key provisions:

Production target: The policy establishes a goal of achieving a Green Hydrogen production capacity of 1 million metric tons per annum (MMTPA) by 2028.

Employment generation: By 2028, the policy aims to create 120,000 new jobs, thereby supporting employment and broader socio-economic development.

Capital subsidies:

- A general capital subsidy ranging from 10% to 30% is available, with the specific rate determined by the geographical location of the investment within the state.
- For the first five Green Hydrogen projects (excluding those located within the Meerut division), a capital subsidy of up to 40% of the total investment is offered, subject to a maximum limit of INR225 crore per project per year.

Land allotment:

- Long-term leases on government or revenue land will be facilitated for project development.
- For government Public Sector Units (PSUs), the lease rate is fixed at INR1 per acre per year.
- For private sector participants, the lease rate is set at INR15,000 per acre per year.

Research and Development: To further establish Uttar Pradesh as a center of innovation in Green Hydrogen, the policy mandates the creation of two State Centres of Excellence (SCoEs) dedicated to advancing research, development, and innovation in the sector.

Maharashtra Harit Hydrogen Policy, 2023

The Maharashtra Harit Hydrogen Policy, 2023, is an innovative initiative designed to establish the state as a leader in Green Hydrogen production and usage. It aims to drive decarbonization in key industrial and energy sectors while promoting the growth and export of Green Hydrogen and its derivatives. To support these goals, the policy provides a broad range of incentives to encourage investment and develop a robust Green Hydrogen ecosystem.

Objectives and key provisions:

Production target: Achieve a Green Hydrogen production capacity of 500 KTPA by 2030.

Decarbonization strategy: Promote the accelerated adoption of Green Hydrogen to reduce carbon emissions across industrial and energy sectors.

Export promotion: Facilitate the development and export of Green Hydrogen products, positioning Maharashtra as a significant player globally.

Capital cost subsidies: 30% subsidy on capital costs for:

- The first three anchor Green Hydrogen production projects.
- The initial 500 hydrogen fuel-cell passenger vehicles for Maharashtra State Road Transport Corporation (MSRTC), capped at Rs.60 lakh per vehicle.
- Establishment of Hydrogen Refueling Stations (HRS), capped at INR4.5 crore per station.
- Construction of hydrogen pipelines up to 10 km, capped at IR2.5 crore.

Other financial support:

- 1% interest subsidy for hydrogen transport projects.
- Full exemption from stamp duty on land conversion.
- 60% reduction in electricity transmission and wheeling charges for 10 years.
- Exemptions and waivers on electricity duties and surcharges.

Operational grants: $0.59/kg grant for blending Green Hydrogen with CNG/PNG for vehicles, available for five years.

Renewable Energy mandate: Requires the use of 100% renewable energy for Green Hydrogen production, aligning with state and national clean energy goals.

West Bengal Green Hydrogen Policy, 2023

The *West Bengal Green Hydrogen Policy*, 2023 is a forward-looking initiative designed to establish the state as a prominent leader in the emerging Green Hydrogen and green ammonia industries. This policy aims to create a supportive environment for investment, foster technological innovation, and generate sustainable employment opportunities. However, the policy has not mentioned a clear Green Hydrogen production target but provides a broad range of incentives to support the development of Green Hydrogen ecosystem in the state.

Objectives and key provisions:

Demand mapping and investment promotion: The policy focuses on identifying potential demand centers for Green Hydrogen and green ammonia through GIS mapping tools, while actively encouraging investment in production infrastructure across West Bengal.

Advancement of technological innovation: A State Centre of Excellence (SCoE) is proposed to spearhead research and development activities, promote techno-economic innovations, and serve as a benchmark institution for other states pursuing similar objectives.

Market development and trade facilitation: The policy aims to establish effective procurement and trading frameworks for Green Hydrogen and green ammonia, ensuring efficient resource allocation and enhanced market accessibility.

Employment generation and skill development: Leveraging the growth of the Green Hydrogen and ammonia sectors, the policy prioritizes the creation of jobs and upskilling of the workforce within the state.

Fiscal incentives:

- 100% exemption from stamp duty and land conversion charges throughout the policy period.
- Complete waiver of electricity duty for the duration of the policy.

Power and energy support: The policy allows production units to bank renewable energy for up to 30 days, optimizing energy utilization and lowering operational costs for Green Hydrogen and ammonia facilities.

Andhra Pradesh Green Hydrogen and Green Ammonia Policy, 2023

The Andhra Pradesh Green Hydrogen and Green Ammonia Policy, 2023 is a strategic initiative aimed at leveraging the state's abundant renewable energy resources to establish a strong ecosystem for Green Hydrogen and green ammonia production. The policy focuses on attracting significant investment, driving job creation, and supporting the development of essential manufacturing infrastructure.

Objectives and key provisions:

Production targets: The policy aims to achieve a production capacity of 0.5 MMTPA of Green Hydrogen or 2.0 MMTPA of green ammonia within the next five years.

Employment generation: A primary objective is to create approximately 12,000 jobs for every MMTPA of Green Hydrogen production within Andhra Pradesh.

Financial benefits:

- 100% reimbursement of net State Goods and Services Tax (SGST) revenue from sales of Green Hydrogen and green ammonia within the state.
- Full exemption from electricity duty on power consumed from renewable energy sources.
- 25% reimbursement of intrastate transmission charges, capped at Rs.10 lakh per MW per year based on electrolyzer capacity.
- Reimbursement of cross-subsidy surcharges for renewable energy drawn within the state.

Infrastructure and connectivity:

- Priority grid connectivity for renewable energy plants dedicated to Green Hydrogen and green ammonia production, with technical feasibility decisions within 21 days.
- Land allotment on a priority basis at a lease rate of INR31,000 per acre per year, escalating by 5% every two years.
- 100% exemption from stamp duty and land use conversion charges.

The policy supports the promotion of manufacturing facilities for Green Hydrogen, green ammonia, and related equipment, contributing to the development of an integrated value chain. In addition to this, Andhra Pradesh Green Hydrogen Valley Declaration-2025, released in July 2025, outlines the following targets:

- Establishing 5 GW of Electrolyzer manufacturing capacity by 2029.
- Achieving 1.50 MMTPA of Green Hydrogen production (revised from 0.5 MMTPA mentioned in GH2 and GA policy).

Odisha Renewable Energy Policy, 2022

The Odisha Green Hydrogen Initiative, embedded within the Odisha Renewable Energy Policy, 2022 and supported by the Industrial Policy Resolution, 2022, is strategically crafted to leverage the state's abundant renewable energy resources and establish Odisha as a prominent Green Hydrogen producer. Currently, Odisha is a preferred choice of the GH2/ GA developers owing to the benefits provided by the state.

Key provisions:

Power-related incentives: Recognizing the high electricity costs in Green Hydrogen production, the policy offers significant power-related benefits:

- **Power tariff rebate:** A reimbursement of INR3.00 (US$0.035) per unit of electricity consumed from local distribution companies or GRIDCO, available for 20 years from the commencement of commercial operations.
- **Electricity duty exemption:** Complete exemption from electricity duty for a 20-year period starting from commercial production.

Non-power-related incentives: To stimulate investment and expansion, the policy provides key non-power incentives:

- **Capital subsidy:** A 30% subsidy on capital investment in Green Hydrogen projects designated as a thrust sector under the Industrial Policy Resolution, 2022.
- **SGST reimbursement:** Full reimbursement of net SGST for the first five years from the date of fixed capital investment, capped at 200% of the plant and machinery cost.

Rajasthan Green Hydrogen Policy, 2023

The Rajasthan Green Hydrogen Policy, 2023, represents a pioneering effort to harness the state's abundant renewable energy resources and establish Rajasthan as a leading Green Hydrogen producer. The policy is structured to attract investment, drive decarbonization, and enable sector growth through a combination of power-related and non-power-related incentives. Rajasthan has released Integrated Clean Energy Policy, 2024 supporting the Green Hydrogen ecosystem superseding the previous GH2 policy

Objectives and key incentives:

Production target: Rajasthan aims to develop a Green Hydrogen production capacity of 2 MTPA by 2030.

Power-related incentives:

- **Transmission and Wheeling charges:** A 50% waiver on intrastate transmission and wheeling charges for power generated from solar or wind plants (with or without storage) for an initial capacity of 500 KTPA, valid for 10 years.
- **Electricity Duty (ED):** A 50% reduction in electricity duty applicable for the same capacity and duration.
- **Surcharge exemptions:** Full exemption from cross-subsidy surcharge (CSS) and additional surcharge (AS) when green energy is utilized for Green Hydrogen or green ammonia production.

Non-power-related incentives: Leveraging provisions from the Rajasthan Investment Promotion Scheme (RIPS), 2022, the policy offers flexible non-power incentives:

- **SGST reimbursement:** 75% reimbursement of net SGST for a period of seven years from commercial production commencement, subject to applicable annual ceilings.
- **Capital subsidy:** An optional capital subsidy ranging between 13% and 28% of fixed capital investment over 10 years, with eligibility determined by investment size, employment generation, and area classification.
- **Turnover-linked incentive:** An alternative incentive providing 1.2% to 2% of net sales turnover over 10 years, also based on investment scale, employment impacts, and regional specifics.

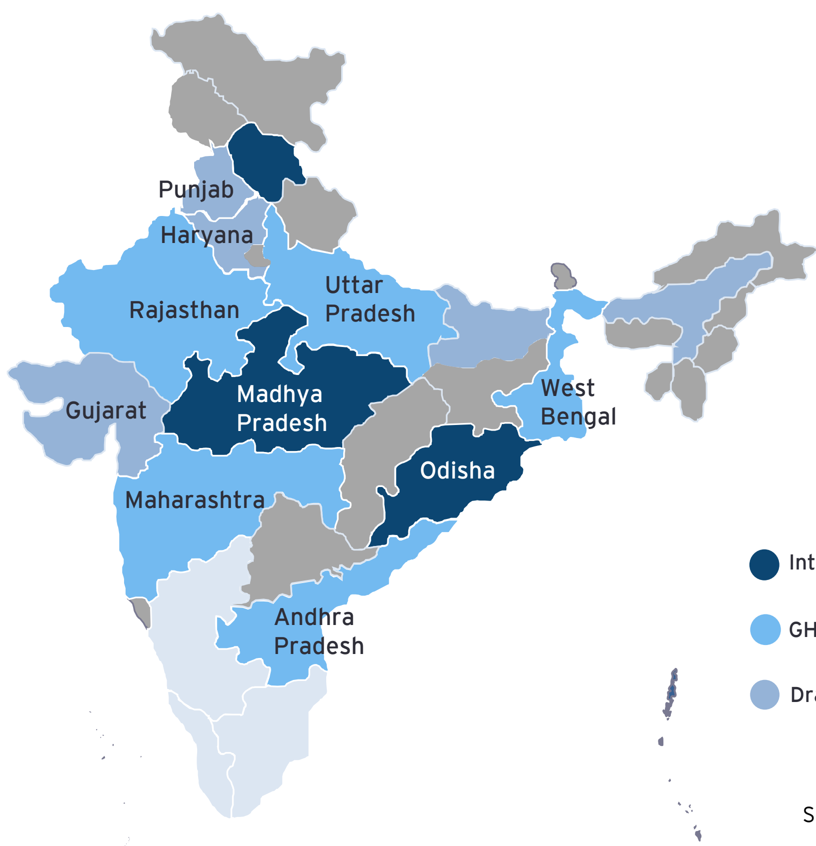
Apart from the states mentioned above, some other states as well are directly or indirectly supporting the Green Hydrogen developments in the country.

Gujarat: The state has not announced any Green Hydrogen policy yet, but is emerging as a premier producer of Green Hydrogen and related derivatives. The state has secured notable investment commitments from key industry players to advance Green Hydrogen projects. Kandla emerged as a hotspot for the GH2/GA developers and recently, Kandla Port has commissioned a 5MW Green Hydrogen project.

Haryana and Punjab: These states are in the process of formulating dedicated policies to support the Gren Hydrogen development.

Madhya Pradesh, Telangana, Chhattisgarh, Bihar and Assam: These states have incorporated Green Hydrogen in their respective clean/ renewable energy policies.

Figure 5: State wise Green Hydrogen policy status



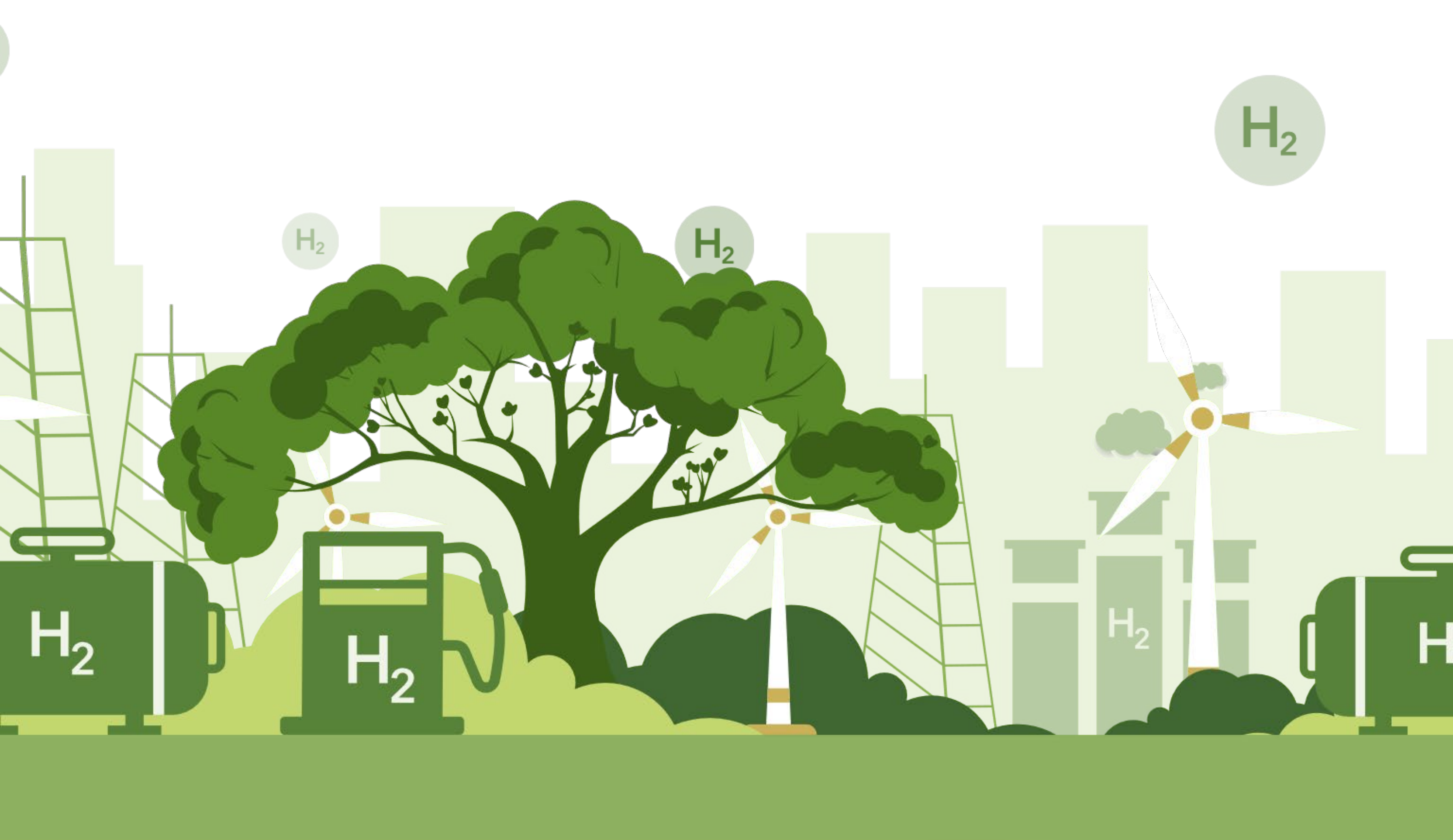
Source - EY analysis

Regulatory and Standards framework

India has initiated a comprehensive effort to establish and implement regulations, codes, and standards to support the safe and efficient deployment of Green Hydrogen across the value chain. A Working Group supported by six sector-specific sub-groups focusing on hydrogen production, storage, transportation, mobility, aviation, shipping, and railways has been formed. Based on the recommendation of these sub-groups, more than 160 standards have been recommended, with 111 already published.

The key regulatory bodies involved in the formulation of standards include:

- Bureau of Indian Standards (BIS)
- Petroleum and Explosives Safety Organisation (PESO)
- Petroleum and Natural Gas Regulatory Board (PNGRB)
- Oil Industry Safety Directorate (OISD)
- Ministry of Road Transport and Highways (MoRTH)



There are other bodies that contribute to the formulation of regulations for the Green Hydrogen domain and are part of various sub-groups based on expertise, such as IOCL, NTPC, GAIL, Railway Board, Cochin Shipyard Ltd and experts from industries, etc. The efforts are ongoing to review, develop, and approve the remaining standards, with an emphasis on international alignment, industry collaboration, and capacity building. This regulatory framework forms a critical foundation for scaling hydrogen adoption, ensuring safety, and aligning with global best practices as part of India's broader energy transition agenda.

In addition to the formulation and adoption of standards, India has established **comprehensive regulatory frameworks,** including:

- Green Hydrogen certification standards defining production thresholds
- Safety evaluation protocols for hydrogen fuel cell vehicles
- Grid connectivity standards for electrolyzers
- Single-window clearance systems for project approvals

Green Hydrogen plant will increase peak electricity demand by 67 GW to 409 GW by 2030, requiring enhanced grid flexibility of 1,100 MW/min for the top 10% of hours. The total investment requirement for the Green Hydrogen ecosystem is estimated at Rs. 10.6 lakh crore, with 71% allocated to renewable energy deployment.

International competitive landscape

India faces intense **global competition** in the Green Hydrogen sector. China leads global production with 20 million tons output, accounting for one-third of global production. The US, following the Inflation Reduction Act, is positioned to achieve production costs of US$0.5-1.5 per kg, potentially growing to 30-35 MTPA by 2030.

However, India's competitive advantages include unified grid infrastructure, abundant renewable resources, skilled workforce, competitive labor costs, and strategic geographical positioning for exports to Europe and East Asia.

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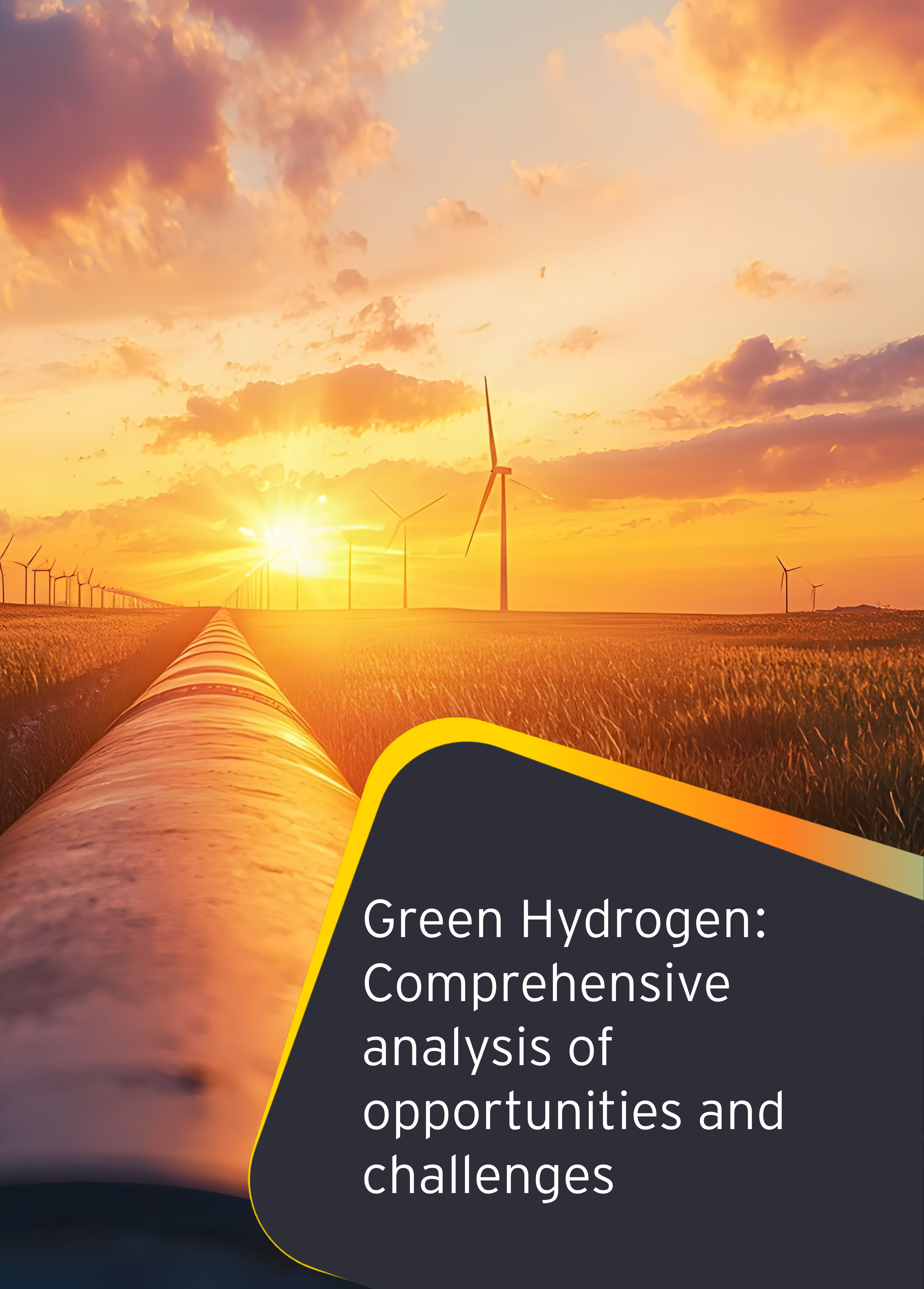

Green Hydrogen: Comprehensive analysis of opportunities and challenges

Technological landscape and innovation

Electrolyzer technology developments

The electrolyzer industry represents the cornerstone of Green Hydrogen production, with three primary technologies competing for market dominance. Alkaline water electrolysis (AWE) currently accounts for approximately 52% of global manufacturing capacity, followed by proton exchange membrane (PEM) electrolysis at 42%, and solid oxide electrolyzer cells (SOEC) at 6%.

Alkaline electrolyzers

remain the most cost-effective solution for large-scale industrial applications. These systems typically achieve efficiency rates of 60%-65% and offer superior durability with operational lifespans of up to 90,000 hours. Recent technological improvements have addressed historical limitations, with modern alkaline systems achieving competitive efficiency levels while maintaining significant cost advantages over PEM alternatives.

PEM electrolyzers

excel in applications requiring rapid response to intermittent renewable energy sources. Despite higher capital costs due to expensive catalysts including platinum and iridium, PEM systems offer superior efficiency rates of 70%-80% and faster startup capabilities. However, their shorter operational lifespans of approximately 40,000 hours and complex maintenance requirements present ongoing challenges.

Solid oxide electrolyzer cells (SOEC)

represent the frontier of electrolyzer technology, operating at high temperatures (700-850°C) and achieving remarkable efficiency rates of up to 84%. SOEC systems can utilize waste heat from industrial processes, potentially improving overall system efficiency. However, material degradation at high temperatures and limited commercial deployment remain significant barriers to widespread adoption.

Recent breakthrough innovations include the development of advanced catalysts that reduce dependence on precious metals, with some research showing 150% improvements in hydrogen production efficiency. Few companies are implementing artificial intelligence and digital twin technologies to enhance electrolyzer performance and reduce operational costs.

Renewable energy integration

The integration of renewable energy sources with hydrogen production systems presents both opportunities and technical challenges. Modern electrolyzers must accommodate the intermittent nature of solar and wind power while maintaining operational efficiency. Advanced control systems now enable electrolyzers to operate effectively at loads as low as 5% to 10% of nominal capacity, significantly improving compatibility with variable renewable energy sources.

India's renewable energy infrastructure provides a compelling case study, with over 223 GW of installed capacity including 108 GW from solar and 51 GW from wind. The country's "One Nation-One Grid-One Frequency" system creates a stable platform for large-scale hydrogen production, while pumped hydro storage (PHS) and battery energy storage systems (BESS) enable round-the-clock renewable energy availability.

The development of dedicated renewable energy projects for hydrogen production is accelerating globally. Projects like Australia's HyEnergy and Europe's REPowerEU initiative demonstrate the potential for gigawatt-scale renewable-powered electrolyzer deployment. These integrated systems combine wind and solar generation with advanced storage technologies to ensure consistent hydrogen production.

Industrial applications and market opportunities

Steel industry transformation

The steel industry represents one of the most promising applications for Green Hydrogen adoption, with hydrogen-based direct reduced iron (H2-DRI) technology offering up to 90% emissions reduction compared to traditional coal-based processes. Global steel production accounts for approximately 7% of annual greenhouse gas emissions, making decarbonization efforts critical for climate goals.

Several major steelmakers have initiated large-scale H2-DRI projects. Sweden's H2 Green Steel has raised €6.5 billion to fund the world's first large-scale green steel plant, powered by Europe's first gigawatt-scale electrolyzer plant. ArcelorMittal has commissioned hydrogen-powered steel plants in Germany, demonstrating the commercial viability of H2-DRI technology.

The transition faces significant economic challenges, with steelmakers requiring low-carbon hydrogen at US$2-3/kg to achieve cost competitiveness, substantially lower than current Green Hydrogen production costs of US$4-8/kg. Despite these hurdles, India's steel sector has initiated pilot projects demonstrating technical feasibility, while the European Union's revised Renewable Energy Directive mandates 42% renewable hydrogen use by 2030, increasing to 60% by 2035.

Ammonia and fertilizer production

The fertilizer industry consumes approximately 185 million tons of ammonia annually, with 70% used for fertilizer production. Each ton of ammonia production requires roughly 178 kg of hydrogen, traditionally sourced from fossil fuel reforming processes that generate significant CO2 emissions.

Converting ammonia synthesis to Green Hydrogen presents substantial decarbonization opportunities. In India, transitioning 19.1 million tons per annum of ammonia production to Green Hydrogen could avoid 30.6 million tons of annual CO2 emissions. Technology providers including Haber Topsoe indicate that existing ammonia manufacturing plants can accommodate up to 10% Green Hydrogen blending with minimal modifications, providing a pathway for gradual transition.

The mature global ammonia trade infrastructure, with over 75 years of handling experience, positions ammonia as an attractive hydrogen carrier for international trade. Ammonia's existing storage and transportation networks could facilitate rapid scaling of Green Hydrogen derivative markets.

Petroleum refining applications

The petroleum refining industry represents the largest current hydrogen consumer, utilizing approximately 95 million tons annually for hydrotreating, hydrocracking, and desulfurization processes. Refineries use hydrogen to reduce sulfur content in diesel fuels and convert heavy crude oil fractions into lighter, more valuable products.

Green Hydrogen adoption in refining faces unique challenges due to the industry's scale and cost sensitivity. Current hydrogen production via steam methane reforming costs $1.9-2.4/kg, while Green Hydrogen alternatives cost US$3.5-5/kg. However, increasing environmental regulations and carbon pricing mechanisms are improving the economic case for Green Hydrogen adoption.

The REFHYNE project in Germany demonstrates the potential for integrating large-scale electrolyzers at refineries to produce Green Hydrogen onsite. This approach reduces transportation costs and ensures supply security while contributing to refinery decarbonization goals.

Transportation sector evolution

Fuel Cell Electric Vehicles (FCEVs)

The global Fuel Cell Electric Vehicles (FCEVs) market is projected to grow from US$0.2 billion in 2024 to US$2.1 billion by 2030, representing a CAGR of 48%. FCEVs offer distinct advantages over battery electric vehicles, including rapid refueling (under five minutes), extended driving ranges exceeding 300 miles, and superior performance in heavy-duty applications.

Current FCEV deployment remains concentrated in specific markets, with Japan, South Korea, California, and Europe leading adoption. Global hydrogen refueling infrastructure has expanded to over 3,000 stations, though this remains insufficient for widespread FCEV deployment. The total cost of ownership for FCEVs is projected to achieve parity with internal combustion engine vehicles by 2030.

Heavy-duty transportation presents the most promising near-term market for FCEVs, with trucks expected to contribute approximately 40% of hydrogen mobility demand by 2030. The weight and range limitations of battery systems make hydrogen fuel cells particularly suitable for long-haul trucking, where rapid refueling and extended range are critical operational requirements.

Maritime and aviation applications

The maritime industry is exploring hydrogen as a solution for decarbonizing international shipping, which accounts for approximately 3% of global greenhouse gas emissions. Hydrogen fuel cells offer zero-emission operation with only water vapor as a byproduct, making them attractive for coastal shipping, ferries, and offshore support vessels.

Recent developments include Asia's launch of the first hydrogen-powered cargo ship utilizing advanced liquid hydrogen fuel cells for propulsion. Major ports are installing hydrogen bunkering stations to support the growing fleet of zero-emission vessels. However, hydrogen's low volumetric energy density necessitates larger storage systems, impacting ship design and cargo capacity.

Aviation applications remain in early development phases, with Airbus' ZeroE prototype completing successful test flights using hydrogen fuel cells. The aviation industry faces unique challenges due to weight constraints and safety requirements, but hydrogen offers the potential for zero-emission flight operations that battery systems cannot match for longer-range aircraft.

Energy storage and grid applications

Long-duration energy storage

Hydrogen's role as a long-duration energy storage medium addresses critical grid stability challenges as renewable energy penetration increases. Unlike battery systems limited to hours of storage, hydrogen can provide seasonal storage capabilities, storing excess renewable energy for months and releasing it when demand peaks or renewable generation decreases.

Power-to-gas-to-power systems utilize excess renewable electricity to produce hydrogen via electrolysis, storing it for extended periods, and converting it back to electricity through fuel cells or hydrogen-capable gas turbines. This process achieves round-trip efficiencies of 35% to 45%, which, while lower than batteries, becomes economically attractive for storage durations exceeding 12 hours.

Grid stabilization applications are gaining momentum, with hydrogen fuel cells providing ancillary services including frequency regulation and voltage support. The Shinincheon Bitdream Hydrogen Fuel Cell Power Plant in South Korea demonstrates large-scale grid integration, producing 78.96 MW while also providing district heating and air purification services.

Power generation integration

Hydrogen-capable gas turbines represent a critical bridging technology for power generation decarbonization. Companies like Siemens Energy and GE Vernova have developed turbines capable of burning hydrogen blends up to 100%, enabling existing thermal power infrastructure to transition toward zero-carbon operation.

Hydrogen co-firing in existing natural gas power plants can begin with blends of up to 25% by volume without significant modifications, providing an immediate pathway for emissions-reduction while maintaining grid reliability. Higher hydrogen concentrations require specialized materials and safety systems but offer the potential for complete decarbonization of thermal power generation.

The integration challenges include hydrogen supply logistics, storage requirements, and operational safety considerations. However, pilot projects worldwide are demonstrating commercial viability, with some facilities already operating on dedicated hydrogen fuel supplies.

Storage and transportation infrastructure

Storage technology comparison

Hydrogen storage presents unique technical challenges due to the molecule's small size, low density, and high reactivity. Current storage technologies each offer distinct advantages and limitations depending on application requirements.

Compressed gas storage

Compressed gas storage remains the most widely deployed solution, with systems operating at 350-700 bar pressure. These systems achieve 90% storage efficiency but require robust pressure vessels and suffer from relatively low volumetric energy density. Compressed storage is well-suited for transportation applications and short-term stationary storage.

Liquid hydrogen storage

Liquid hydrogen storage achieves higher volumetric density but requires cryogenic temperatures of -253°C, consuming 30% to 36% of the hydrogen's energy content for liquefaction. Despite high energy requirements, liquid storage becomes attractive for large-scale applications and long-distance transportation where weight and volume constraints are critical.

Liquid organic hydrogen carriers (LOHCs)

Liquid organic hydrogen carriers (LOHCs) offer the advantage of utilizing existing liquid fuel infrastructure. LOHC systems can store and transport hydrogen at ambient conditions using organic compounds like toluene or benzyltoluene. However, the dehydrogenation process requires significant energy input (13% to 34% energy loss), and many LOHC compounds raise environmental and safety concerns.

Transportation networks

Global hydrogen pipeline infrastructure remains limited, with current networks totaling only 4,500 km compared to projected needs of 12,000 km by 2030. The development of dedicated hydrogen backbone networks is accelerating, with Europe leading through initiatives like the European Hydrogen Backbone planning 28,000 km of pipelines by 2030.

Repurposing existing natural gas infrastructure offers a cost-effective approach to rapid hydrogen network development. Converting natural gas pipelines for hydrogen transport can reduce costs by up to 70% compared to new construction, though technical challenges including material compatibility and safety systems require careful management.

International hydrogen trade is developing through multiple pathways. Shipping routes using ammonia and LOHCs are expected to cost US$1.9-2.2/kg and US$2.0-2.5/kg respectively, compared to higher costs for liquid hydrogen shipping. Pipeline transport remains the most cost-effective option for distances up to 3,000 km, with costs as low as US$0.35/kg per 1,000 km.

Policy frameworks and investment landscape

Government support mechanisms

Global governments have committed more than US$37 billion in public funding to hydrogen development, while private sector investments have reached approximately US$300 billion. However, significant gaps remain, with emerging markets and developing countries requiring an estimated US$100 billion annually for hydrogen investments between now and 2030.

India's National Green Hydrogen Mission represents one of the most comprehensive policy frameworks, with an initial outlay of INR19,744 crore (US$2.4 billion) targeting 5 million tons of annual Green Hydrogen production by 2030. The mission includes production-linked incentives (PLI) for electrolyzer manufacturing and Green Hydrogen production, along with pilot projects across steel, mobility, and shipping sectors.

State-level policies in India provide additional incentives potentially worth US$61 billion, with power-related support accounting for 63% of total incentives. States like Uttar Pradesh offer capital subsidies up to 40% for initial projects, while Rajasthan provides 50% rebates on transmission charges for the first 500 KTPA of Green Hydrogen capacity.

United States Policy Support through the Inflation Reduction Act offers up to US$3/kg tax credits for Green Hydrogen production over 10 years, significantly improving project economics. The Department of Energy's hydrogen hub program has allocated US$9.5 billion to establish regional hydrogen ecosystems across the country.

European Union Initiatives include the REPowerEU plan with US$544 billion committed to energy independence and Green Hydrogen deployment. The EU targets 20 million tons of annual hydrogen consumption by 2030, with half sourced from imports, driving international trade development.

Financial mechanisms and investment barriers

Development finance institutions have identified several key barriers limiting hydrogen investment flows. High upfront capital requirements, technological risks, and uncertain demand create challenging investment environments, particularly in emerging markets. Blended finance mechanisms combining public and private capital are emerging as critical tools for risk mitigation.

Guarantees and insurance products have proven effective in renewable energy deployment, mobilizing 45% of private finance despite representing only 5% of climate finance commitments. Similar mechanisms are being developed for hydrogen projects, though the nascent industry presents unique risk profiles requiring specialized financial products.

Carbon pricing and fossil fuel subsidy reform are identified as critical policy tools for improving Green Hydrogen competitiveness. Current fossil fuel subsidies of approximately US$5.9 trillion annually create significant barriers to clean hydrogen adoption. Several jurisdictions are implementing carbon border adjustment mechanisms to level the playing field for low-carbon hydrogen.

Economic impact and job creation

Employment generation potential

The hydrogen economy presents substantial job creation opportunities across the entire value chain. According to an analysis, the US hydrogen industry could generate US$750 billion in annual revenue and support 3.4 million jobs by 2050. Globally, hydrogen deployment could generate up to 30 million jobs by 2050, with a US$2.5 trillion annual revenue boost to economies worldwide.

India's employment projections under the National Green Hydrogen Mission include creating over 600,000 jobs by 2028, with Uttar Pradesh alone targeting 120,000 positions through Green Hydrogen development. The mission's comprehensive approach spans manufacturing, research and development, operations, and supporting services.

The hydrogen industry creates diverse employment opportunities requiring various skill levels. Unlike some high-tech industries requiring exclusively advanced degrees, hydrogen applications include positions for trade certifications, associate degrees, and on-the-job training alongside high-skilled engineering and scientific roles. This diversity makes hydrogen development accessible to broader workforce segments.

Regional economic impacts vary significantly based on existing industrial infrastructure and policy support. The US Department of Energy analysis indicates that regions with established energy industries, such as the Upper Midwest and Gulf Coast, show the highest job creation potential, with net employment increases of 0.44% to 0.56% by 2050.

Skill development and workforce transition

The transition to a hydrogen economy requires substantial workforce development initiatives. An estimated 630,000 workers will need hydrogen-related skills by 2050 in the US automotive sector alone, with many entering the workforce during the market expansion period. Similar workforce transformations are expected across steel, chemical, and energy sectors globally.

Training programs must address both new hydrogen-specific technologies and the adaptation of existing skills for hydrogen applications. For example, natural gas industry workers possess transferable skills for hydrogen pipeline operations, while automotive technicians can adapt their expertise for Fuel Cell Electric Vehicle maintenance.

Educational institutions are developing specialized curricula for hydrogen technologies. Universities are establishing research programs and degree concentrations in hydrogen engineering, while community colleges are creating certificate programs for technical roles. However, significant gaps remain in preparing the workforce for the anticipated scale of hydrogen deployment.

Challenges and barriers to adoption

Cost competitiveness challenges

The fundamental barrier to widespread Green Hydrogen adoption remains cost competitiveness. Current production costs of US$3.5-5/kg must decrease by more than half to compete with grey hydrogen at US$2.0-2.5/kg. This cost reduction requires simultaneous improvements across the entire value chain, including renewable electricity costs, electrolyzer capital expenditure, and operational efficiency.

Renewable energy costs

account for 60% of current Green Hydrogen production expenses. While renewable electricity costs have declined significantly, further reductions of 40% to 50% are necessary to achieve cost parity with fossil-based hydrogen. Battery storage costs, representing 20% to 25% of renewable system expenses, have dropped 30% to 40% in recent years but require additional decreases to meaningfully impact overall hydrogen costs.

Electrolyzer cost reduction

has slowed in recent years, with only 20% cost reductions between 2021-2024 compared to 42% decreases from 2010-2020. Achieving target costs requires breakthrough innovations in materials science, manufacturing processes, and system design. Current electrolyzer efficiencies of 60% to 65% must improve to over 80% while capital costs decrease substantially.

Infrastructure investment requirements

create additional economic barriers. Global hydrogen pipeline networks need expansion from 4,500 km to 12,000 km by 2030, requiring massive capital investments. Storage facilities must increase from 200 globally to 1,000 by 2030, while refueling stations need to grow from approximately 1,000 to 10,000 stations.

Technical and safety challenges

Hydrogen's unique physical and chemical properties create ongoing technical challenges across the value chain.

Material compatibility issues arise from hydrogen embrittlement of steel and other materials, requiring specialized alloys and design considerations for pipelines, storage vessels, and processing equipment.

Safety considerations encompass hydrogen's wide flammability range, invisible flame characteristics, and tendency for leakage due to its small molecular size. Comprehensive safety standards are being developed globally, with organizations like NASA, NFPA, and ISO creating guidelines for hydrogen system design, operation, and emergency response procedures.

Quality and purity standards remain inconsistent globally, creating barriers to international trade. Different applications require varying hydrogen purity levels, from 99.95% for fuel cells to lower purities for industrial processes. Standardization efforts are underway, but harmonized global standards are still lacking.

Regulatory and market development barriers

- **Regulatory frameworks** lag technological development in many jurisdictions. Existing regulations often fail to address hydrogen-specific applications, creating uncertainty for project developers and investors. The absence of globally harmonized standards for Green Hydrogen classification and verification creates additional market barriers.
- **Demand creation challenges** persist despite growing policy support. Many potential hydrogen users remain hesitant due to cost premiums and supply uncertainties. Creating sufficient market demand requires coordinated policies including mandates, carbon pricing, and public procurement programs.
- **Supply chain Dependencies** on critical materials present ongoing risks. Electrolyzer manufacturing requires materials like platinum, iridium, and rare earth elements, creating potential supply bottlenecks and price volatility. Efforts to develop alternative materials and diversify supply sources are crucial for sector growth.

Future outlook and strategic recommendations

Market growth projections

The Green Hydrogen market is positioned for exponential growth, with global demand projections ranging from 125-585 million tons annually by 2050. Near-term growth will be concentrated in Europe, Japan, and South Korea, which are expected to account for approximately 30% of new clean hydrogen demand by 2030.

- **Technology cost trajectories** indicate substantial improvements ahead. Green Hydrogen production costs could decrease to US$1.37/kg by 2030 in optimized scenarios, while Indian production costs are projected to fall to INR260-310/kg (US$3-3.75/kg) with government support. Electrolyzer costs could decrease by 45% by 2030 and 70% by 2050 compared to current levels.
- **Infrastructure development** will accelerate significantly, with the European Hydrogen Backbone planning 50,000 km of pipelines by 2040, consisting of approximately 60% repurposed and 40% new infrastructure. Global electrolyzer manufacturing capacity is projected to reach 165-520 GW by 2030, up from current capacity of approximately 50 GW.

International trade development

Global hydrogen trade patterns are emerging with distinct import and export regions. **Major import markets** include Germany, Japan, and South Korea, which have committed to significant hydrogen imports to meet domestic demand. Japan targets 30 million tons annually by 2050, while South Korea projects 177-fold increases from current consumption levels.

- **Export opportunities** are developing in regions with abundant renewable resources and competitive advantage in hydrogen production. India, Australia, Chile, and Middle Eastern countries are positioning themselves as major exporters, with India's export potential reaching 1.1 million metric tons annually.
- **Trade infrastructure** development includes specialized shipping capabilities for hydrogen derivatives and pipeline networks for regional trade. The development of ammonia and LOHC shipping routes enables long-distance hydrogen trade, while regional pipeline networks facilitate continental distribution.

Research and development priorities

- **Breakthrough technology development** remains critical for achieving cost-competitive Green Hydrogen. Priority areas include advanced electrolyzer materials reducing precious metal dependence, improved catalysts increasing efficiency, and novel production pathways like photoelectrochemical water splitting.

  Recent research breakthroughs demonstrate significant potential. Swedish researchers have developed triple-layered materials enhancing photochemical hydrogen production by eight times compared to existing technologies. Stainless steel innovations could revolutionize electrolyzer durability and reduce costs.
- **System integration research** focuses on enhancing renewable energy integration with hydrogen production, developing advanced control systems for variable operation, and improving overall system efficiency. Artificial intelligence and digital twin technologies are being deployed to improve electrolyzer performance and predict maintenance requirements.

Policy recommendations for acceleration

- **Harmonized standards development** represents a critical priority for global market development. International coordination on Green Hydrogen certification, quality standards, and measurement methodologies will facilitate trade and reduce regulatory barriers. Organizations like the International Hydrogen Trade Forum are advancing these efforts through multilateral cooperation.
- **Demand creation policies** should include mandatory blending requirements, carbon pricing mechanisms that account for the full lifecycle emissions of different hydrogen production pathways, and public procurement programs that create early markets for Green Hydrogen applications.
- **Infrastructure investment support** through public-private collaborations can accelerate the development of shared infrastructure including pipelines, storage facilities, and refueling networks. Coordinated regional planning can enhance infrastructure development and reduce overall system costs.
- **International cooperation mechanisms** including technology transfer agreements, development finance coordination, and bilateral trade alliances will be essential for global hydrogen market development. The USA-Germany Climate and Energy Partnership exemplifies effective bilateral collaboration on hydrogen technologies and trade development.

5

Industrial demand of Green Hydrogen

Steel sector

India has significant reserves of high-grade iron ore, including hematite (Fe_2O_3) and magnetite (Fe_3O_4). Currently, steel production primarily utilizes hematite, while magnetite remains underutilized. The steel manufacturing process involves removing oxygen from iron ore using reducing agents such as carbon and hydrogen, along with fluxes to eliminate impurities like alumina and silica. A high-temperature heat source is also essential for reduction reactions and producing molten metal.

Steel production is achieved primarily through two methods: the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and the Electric Arc Furnace (EAF) route.

Blast Furnace-Basic Oxygen Furnace (BF-BOF) route

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Steel production is achieved primarily through two methods: the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and the Electric Arc Furnace (EAF) route.

The blast furnace is an essential part of the steel manufacturing process. It operates by converting iron ore into molten iron through a high-temperature reduction process. The furnace consists of several critical components, including the hearth, bosh, shaft, and top, all of which work in tandem to achieve the desired output.

The primary inputs into a blast furnace in steel plant include iron ore, coke, and limestone. Coke serves as both a fuel and a reducing agent, while limestone helps remove impurities from the ore. These materials are carefully mixed to form the "burden" that enters the furnace.

Coal requirement
800 kg per ton of steel

Energy requirement
20-30 GJ per ton

CO_2 emissions
1.8-2.2 tons per ton of steel

Here is a breakdown of how it works:

Charging:
Introduction of raw materials

The blast furnace starts by adding three key materials: iron ore, coke, and limestone. These are added in layers from the top of the furnace. Iron ore provides the iron, coke serves as fuel and helps break down the ore, and limestone helps remove impurities. This step is crucial for keeping the furnace running smoothly, which is key to blast furnace stability.

Combustion zone:
Coke ignition to generate high temperatures

Next, hot air, or hot blast, is blown into the bottom of the furnace, causing the coke to burn and generate intense heat. This heats the furnace to around 1,600°C. The high temperature is necessary for the next steps of the blast furnace steel making process.

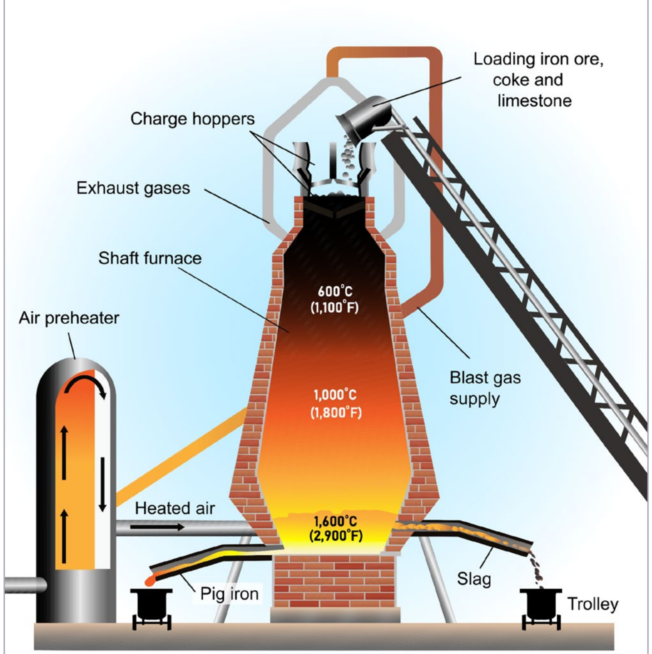
Reduction reaction:
Iron ore reduction to molten iron

In the blast furnace ironmaking process, the fundamental chemical transformation involves the reduction of iron ore (iron oxide) to molten iron. This is achieved when carbon from the coke reacts with the oxygen present in the iron oxide, producing metallic iron and carbon dioxide. The balanced reaction is as follows:

$$Fe_2O_3+3C \rightarrow 2Fe+3CO_2$$

This is indeed how iron is reduced to molten iron in the blast furnace iron production process. This reduction is fundamental to the blast furnace steel making process.

Figure 6: Blast furnace



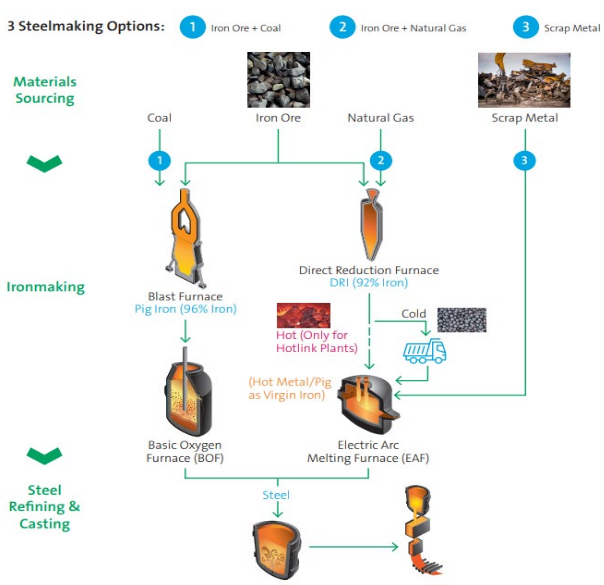
Slag formation: Separation of impurities as slag

The formation of slag occurs through the reaction of impurities (such as silica) with limestone to form calcium silicate (slag). The slag floats on top of the molten iron and helps remove impurities, maintaining the quality of the molten iron. It is also true that slag is important for maintaining the blast furnace stability and protecting the blast furnace refractories from damage caused by impurities.

Tapping process: Extraction of molten iron and slag

The tapping process involves extracting molten iron and slag from the blast furnace. Molten iron is tapped through a taphole and directed into ladles for further processing in steelmaking units, such as basic oxygen furnaces. The lighter slag, which floats on top of the molten iron, is removed separately through a different notch or channel. This step is critical for maintaining efficient and continuous blast furnace operations, as timely tapping prevents buildup inside the furnace and ensures uninterrupted steel production.

Figure 7: Steel Production Processes



Source: Air Products (See Ref. No. 64)

Electric Arc Furnace (EAF) route

The DRI process begins with the selection of suitable iron ore, which is usually rich in iron oxides. Raw iron ore is then processed and agglomerated into pellets or briquettes. These iron ore lumps are then subjected to the reduction process.

Direct reduction involves using a reducing gas, primarily consisting of carbon monoxide (CO) and hydrogen (H2). This gas is produced from natural gas or coal. The iron ore and reducing gas are fed into a reactor, where the iron oxides in the ore are chemically reduced to iron by the gas. The output of this reduction process is DRI. Depending on the exact process and ore used, DRI can have iron content as high as over 90%.

DRI is used as a substitute or supplement to scrap in electric arc furnace (EAF) steelmaking. EAFs convert a mixture of scrap steel and DRI to liquid steel

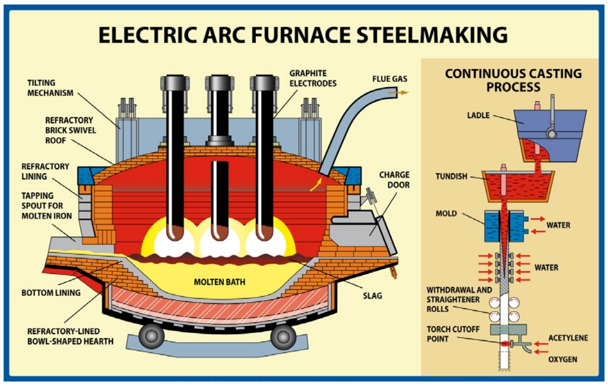
CO_2 emission

245-680 kg per ton

Energy requirement

700 kWH per ton

Figure 8: Electric Arc Furnace



Globally, the BF-BOF route contributes 70% to total steel production, while EAF/ IF accounts for 30%, and there is a growing emphasis on transitioning to EAF due to its reduced carbon footprint.

Current steel production in India

India has emerged as the world's second-largest producer of crude steel, following China. In FY 2023–24, the country's crude steel production reached 144 million tons per annum (MTPA), while finished steel production stood at 139 MTPA. The per capita steel consumption is estimated at 97.7 kg, reflecting steady growth in domestic demand. During the April–October 2024 period alone, crude steel and finished steel production were estimated at 85.4 MTPA and 82.8 MTPA, respectively.

This robust growth is underpinned by a series of policy measures, including the National Steel Policy 2017, which targets a significant increase in production capacity by 2030–31. Additionally, the Production Linked Incentive (PLI) Scheme for Specialty Steel, launched in 2021 with an outlay of INR6,322 crore, aims to boost domestic manufacturing and reduce import dependence. The implementation of the steel Quality Control Order (QCO) has further strengthened quality assurance by curbing the use of sub-standard steel in both domestic and imported supply chains.

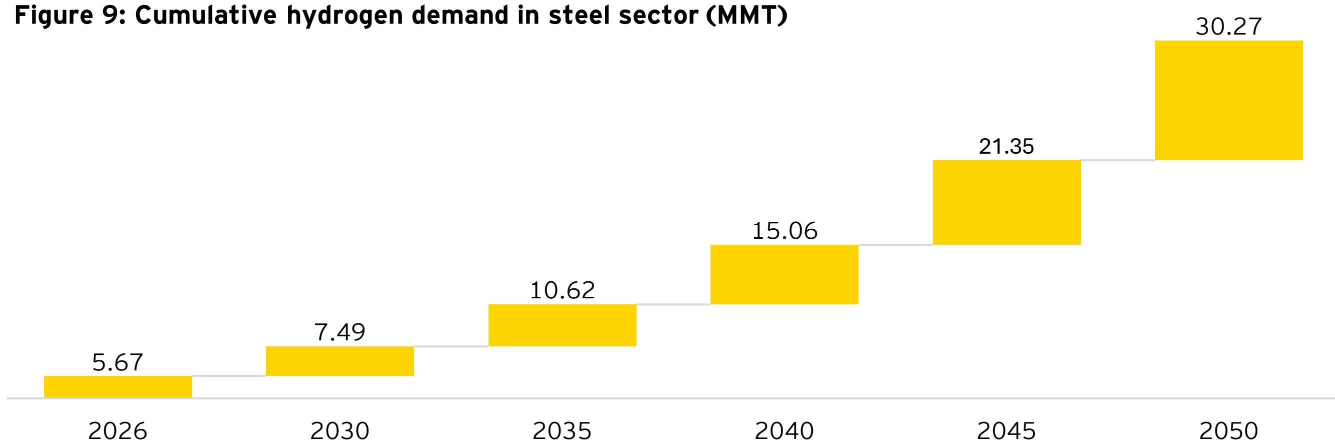
Hydrogen demand in Indian steel sector

Currently, hydrogen is not used in steel production in India. The conventional Blast Furnace–Basic Oxygen Furnace (BF-BOF) process, which is highly energy-intensive and reliant on coal, presents a significant opportunity for decarbonization through the integration of Green Hydrogen. Research and pilot projects have demonstrated that injecting up to 20% hydrogen into the BF-BOF process is feasible, requiring approximately 14 kg of hydrogen per ton of crude steel. Alternatively, using 100% hydrogen for Direct Reduced Iron - Electric Arc Furnace (DRI-EAF) production demands around 65 kg of hydrogen per ton.

India's crude steel production has grown at a compound annual growth rate (CAGR) of 7.23% in recent years. If this growth continues, steel production is projected to reach 235 million tons by 2030 and 950 million tons by 2050.

Assuming that 65% of future steel production will continue via the BF-BOF route and 35% through the DRI-EAF route, the corresponding hydrogen demand is estimated to be approximately 7.5 million metric tons (MMT) by 2030 and 30 MMT by 2050. These figures highlight the immense potential for Green Hydrogen in decarbonizing India's steel sector.

Figure 9: Cumulative hydrogen demand in steel sector (MMT)

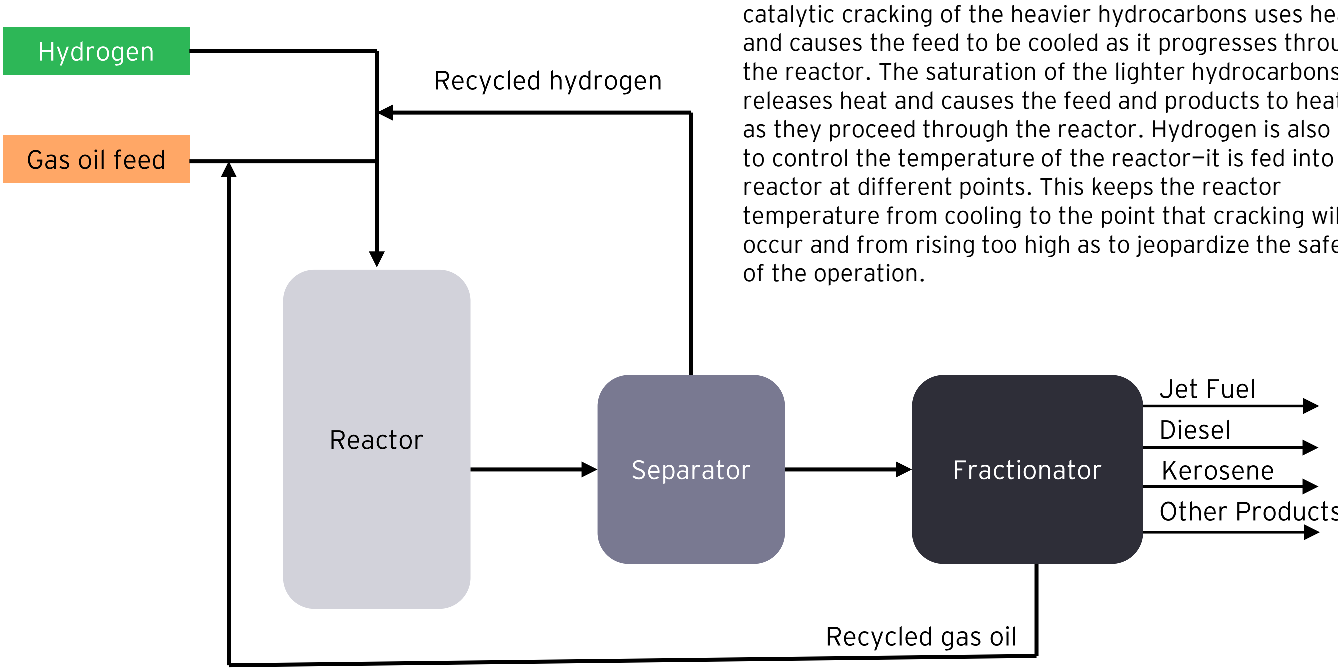


Source - EY analysis

Refinery sector

India's refining sector is one of the largest consumers of hydrogen, predominantly used in hydrocracking and hydrotreating processes to remove impurities like sulfur from petroleum products and to improve fuel quality. Currently, this hydrogen demand is almost entirely met through fossil-fuel-based hydrogen i.e. grey hydrogen, primarily natural gas via steam methane reforming (SMR), leading to significant CO_2 emissions.

Figure 10: Hydrocracking process



Hydrocracking

A hydrocracking unit, or hydrocracker, takes gas oil, which is heavier and has a higher boiling range than distillate fuel oil, and cracks the heavy molecules into distillate and gasoline in the presence of hydrogen and a catalyst. The hydrocracker upgrades low-quality heavy gas oils from the atmospheric or vacuum distillation tower, the fluid catalytic cracker, and the coking units into high-quality, clean-burning jet fuel, diesel, and gasoline.

There are two main chemical reactions occurring in the hydrocracker: catalytic cracking of heavy hydrocarbons into lighter unsaturated hydrocarbons and the saturation of these newly formed hydrocarbons with hydrogen. The catalytic cracking of the heavier hydrocarbons uses heat and causes the feed to be cooled as it progresses through the reactor. The saturation of the lighter hydrocarbons releases heat and causes the feed and products to heat up as they proceed through the reactor. Hydrogen is also used to control the temperature of the reactor—it is fed into the reactor at different points. This keeps the reactor temperature from cooling to the point that cracking will not occur and from rising too high as to jeopardize the safety of the operation.

Hydrotreating

It is common to assume that the hydrotreating process is a single unit operation that converts all of the raw feed into a final desulfurized product. However, this is not the case; most hydrotreatment processes require many unit operations, including a reactor, gas separators, separation columns, and heat exchangers. The process can be divided into three main processing blocks:

- heat exchange network
- reactor in which the actual hydrotreating takes place
- stripping where the desulfurized product stream is separated from the volatiles, gases, and impurities

Each hydrotreating unit is tailored to the feedstock and end product. For instance, the process to hydrotreat naphtha is not the same as the process for diesel fuels. The most common cuts that are hydrotreated in a refinery include: light naphtha, heavy naphtha, jet fuel or kerosene, and diesel oils (e.g., light and heavy coker diesel oil).

The feed is first pressurized and mixed with the recycle and makeup hydrogen streams. The mixture is heated to about 290-430°C before entering the fixed-bed reactor, which operates at about 7-180 bar. Higher temperatures and pressures are used for processing heavier feedstocks, such as diesel oils. Overall, however, hydrotreater temperatures are relatively moderate, which avoids thermal cracking of molecules while being high enough to enable reaction of the feedstock.

Inside the fixed-bed reactor, hydrogenolysis, and mild hydrocracking reactions take place to convert sulfur, nitrogen, oxygen, and other contaminants to hydrogen sulfide, ammonia, water vapor, and other stabilized byproducts.

The catalyst used in the reactor is a crucial design consideration that greatly affects the final products. If sulfur removal is the primary goal, cobalt-molybdenum catalysts are favored. If the crude oil is relatively low in sulfur, nitrogen removal becomes the priority and nickel-molybdenum catalysts are chosen. Depending on the conditions and composition of the outlet streams, the byproducts are either discarded, recycled, or sent for further treatment.

Most outlet streams undergo further treatment to lessen their environmental impact and/or recover the material for use. Sour gas (which contains hydrocarbons, carbon dioxide, and a significant amount of hydrogen sulfide) is commonly sent to an amine gas treating unit that separates the hydrocarbon gases from the hydrogen sulfide and carbon dioxide. During amine treatment, the carbon dioxide and hydrogen sulfide are absorbed by an amine solution in the absorption unit, producing a sweet gas and amine-rich stream. The amine-rich mixture is pumped to a desorption unit where it is recovered as lean amine and recycled. The final product stream is a desulfurized product fuel, commonly called sweet gas.

Hydrotreating naphtha

Naphtha is a valuable product of petroleum refining, as it is one of the main constituents of the gasoline blending pool. While there is no formal definition of naphtha, it is commonly considered the C5–C12 cut, which is divided into light and heavy naphtha. Light naphtha has an initial boiling point (IBP) of about 30°C and a final boiling point (FBP) of about 145°C. It contains most of the hydrocarbons between C4 and C6. Heavy naphtha has an IBP and FBP of about 140°C and 205°C, respectively. It contains most of the hydrocarbons in the C6–C12 range.

High sulfur content is associated with cuts that are heavier than naphtha. However, removing the relatively small amount of sulfur in naphtha is beneficial for engine performance and operational longevity. The below figure presents a flow diagram of the hydrotreating process for naphtha.

Heating: The naphtha feed enters the hydrotreatment unit through a charge pump. It is first mixed with hydrogen gas from either the catalytic reforming unit (CRU) or refinery hydrogen plant. The mixture is then heated to 340°C while being contacted with the reactor's effluent.

The charge heater has four passes with four gas burners. Heater tubes are constructed of Type 321 stainless steel, which is the grade of choice for applications with temperatures up to around 900°C, because it combines high strength and resistance to scaling with resistance to aqueous corrosion.

Reaction: After preheating, the mixture is fed to a reactor with two catalyst beds. The desulfurization reactions take place over the cobalt-molybdenum bed and the nitrogen reactions take place over the alumina bed. The reactor temperature is held at a constant 315°C and a pressure of 370 psig.

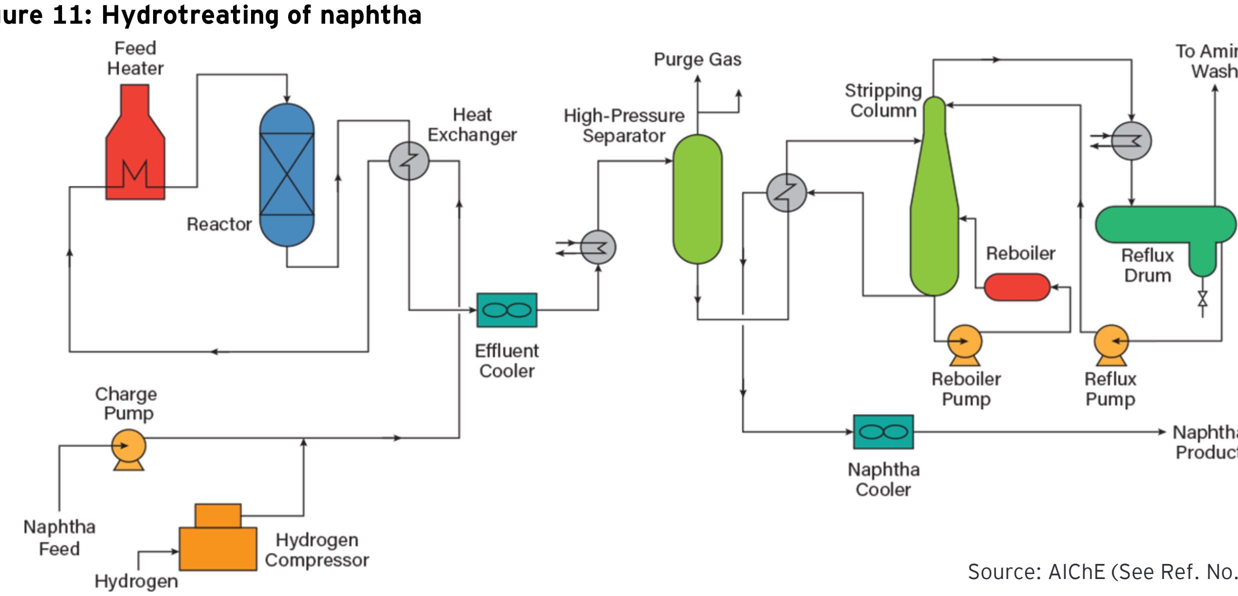
The reactor effluent contains mostly desulfurized naphtha, excess hydrogen, hydrogen sulfide, ammonia, and light hydrocarbons (C1–C4) due to mild cracking. The reactor effluent is cooled and partially condensed through a feed or effluent heat exchanger and then cooled with air.

Separations: The separation process, or stripping section, uses a series of separators and columns to stabilize the naphtha. The cooled stream from the reactor is sent to a pressurized flash separator at 290 psig. The light ends, mainly hydrogen sulfide, ammonia, excess hydrogen gas, and light hydrocarbons, are separated from the bulk of the desulfurized naphtha.

The liquid naphtha stream from the separator is then sent to the stripping unit. The stripping column is heated to 340°C by a reboiler and held at a pressure of 205 psig. High temperature and pressure enable removal of volatile material (light hydrocarbons), which would vaporize at final storage and use conditions. Inlets to the stripping column include desulfurized raw naphtha, recycled desulfurized stripped naphtha, and the bottoms of the column. The outlet streams include mostly light gases (C1–C5 hydrocarbons) that are sent for amine treatment to recover them as fuels.

The resulting liquid naphtha is then cooled by air and sent out of the unit's battery limits as stabilized hydrotreated naphtha product.

Figure 11: Hydrotreating of naphtha



Source: AIChE (See Ref. No. 48)

Hydrotreating diesel oils

Diesel oil may be either a direct cut from the atmospheric distillation column or a mixture of light cycle oil from the fluid catalytic cracker (FCC) unit and heavy cycle oil from the delayed coker. These cuts contain 1% to 2% sulfur (10,000–20,000 ppm)—much higher than the fuel requirement of 10–15 ppm.

Therefore, hydrotreating is one of the most important steps of processing diesel oils to specification, as it removes sulfur and other impurities such as nitrogen and olefins. In addition, hydrotreating saturates olefins (removal of double-bonded carbons) within the diesel oil. This process increases stability and decreases volatility of diesel, enabling longer storage.

The process of hydrotreating diesel oil cuts is much more complex than that of naphtha, primarily due to the addition of the regenerative amine system, which recovers excess hydrogen gas and removes hydrogen sulfide via diethanolamine (DEA). The below figure presents a flow diagram of the hydrotreating process for diesel oil.

Heating: The raw untreated diesel oil is pumped directly to the heat exchange network. Hydrotreating processes are designed with heat exchange networks that pair the low-temperature feed to the reactor, which requires heating, to the high-temperature reactor effluent that requires cooling.

Reaction: The heated feedstock is mixed with a hot recycle hydrogen stream recovered from downstream processes, and the mixture is sent to the reactor. Depending on the sulfur content of the stream, either a cobalt-molybdenum bed (sulfur removal) or nickel-molybdenum on alumina bed (nitrogen removal) will be used. Because high-sulfur fuels are more common in the industry today, sulfur removal is typically the focus of diesel oil hydrotreating.

The effluent of the reactor includes the offgases to be removed in the separator, light ends that will be treated and sent to the naphtha unit, and the unstabilized diesel oils.

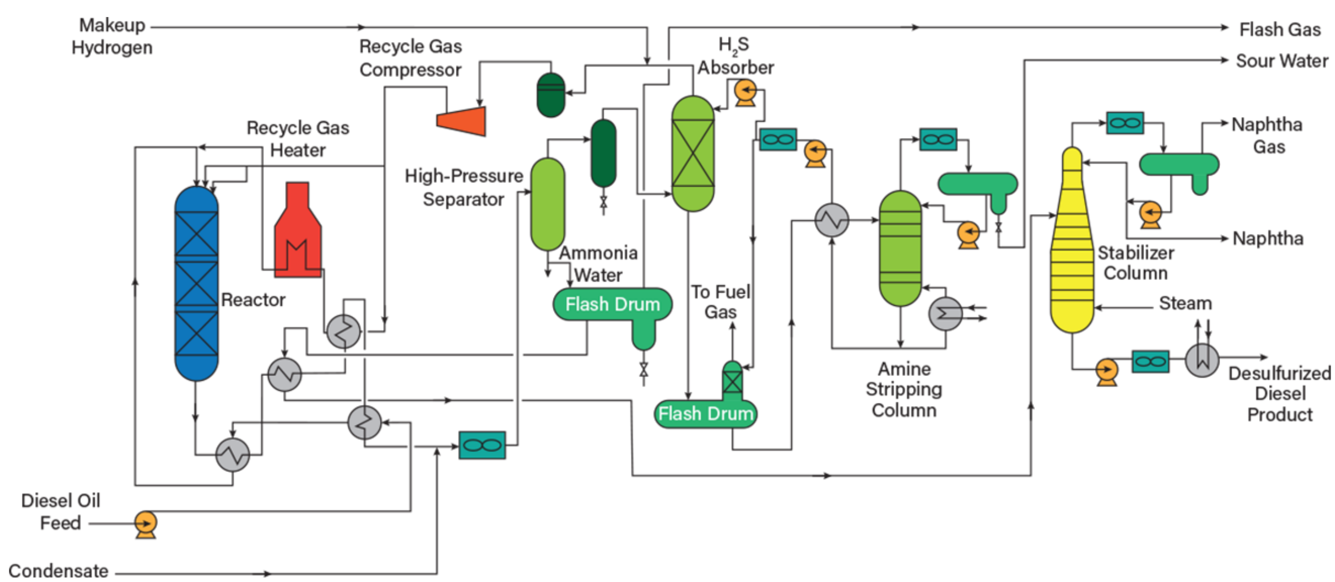
Separations: The reactor effluent is cooled in the heat exchange network, and fresh liquid condensate from lighter cuts of the crude distillation unit is injected into the reactor effluent to avoid salt formation in downstream unit operations. The mixture is then flashed into a high-pressure separator drum, producing a liquid byproduct ammonia solution that is sent to the refinery wastewater system and a hydrogen-rich gas that contains some hydrogen sulfide.

The gases are sent to an absorber that removes the hydrogen sulfide via a circulating DEA solution. The resulting hydrogen stream is combined with makeup hydrogen and is injected into the feedstock stream that enters the initial hydrotreatment reactor.

The now-stabilized diesel oil from the flash drum is depressurized in a successive flash drum. The process of depressurization favors gas formation, further stabilizing the liquid hydrocarbons. The flash gas is sent for hydrogen sulfide removal before going to the refinery's fuel system.

The bottoms liquid stream from the second flash drum is preheated and sent to a stabilizer column. The stabilizer column produces three main cuts: the naphtha gas to be recovered, the recovered naphtha to be combined with other naphtha streams, and the desulfurized stabilized diesel.

Figure 12: Hydrotreating of diesel



Source: AIChE (See Ref. No. 48)

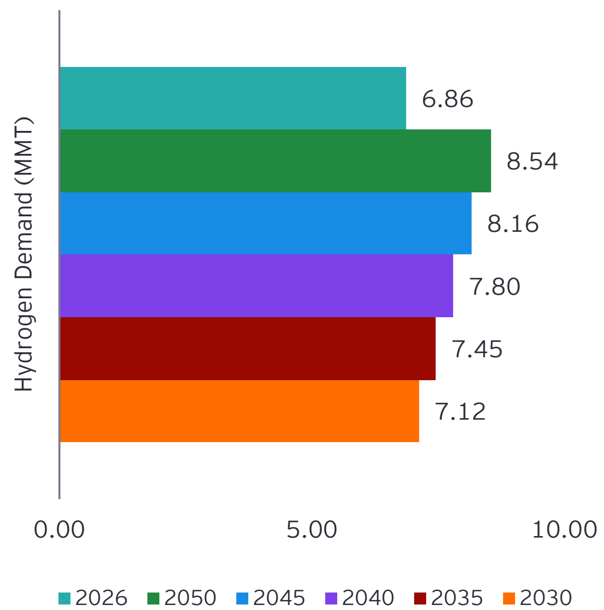
Green Hydrogen demand in refinery sector

According to industry estimates, approximately 26.1 kg of hydrogen is required to process one metric ton (MT) of crude oil.

Based on this ratio, hydrogen demand is directly proportional to the volume of crude oil refined. India's current refining capacity is approximately 258 million metric tons (MMT) per annum. This implies an annual hydrogen demand of roughly 6.74 MMT from the refinery sector in 2024.

India's refining capacity is expected to grow at a compound annual growth rate (CAGR) of 0.92%, in line with both domestic fuel demand and India's ambitions to become a refining hub for exports. Based on this growth trajectory, the projected refining capacity and corresponding hydrogen demand have been developed (see Cumulative Hydrogen Demand in Refinery Sector).

Figure 13: Cumulative Hydrogen Demand in Refinery Sector



Source - EY analysis

The total hydrogen demand in the refinery sector is expected to grow from approximately 6.73 MMT in 2024 to 7.12 MMT by 2030 and 8.54 MMT by 2050, indicating a significant market for Green Hydrogen adoption.

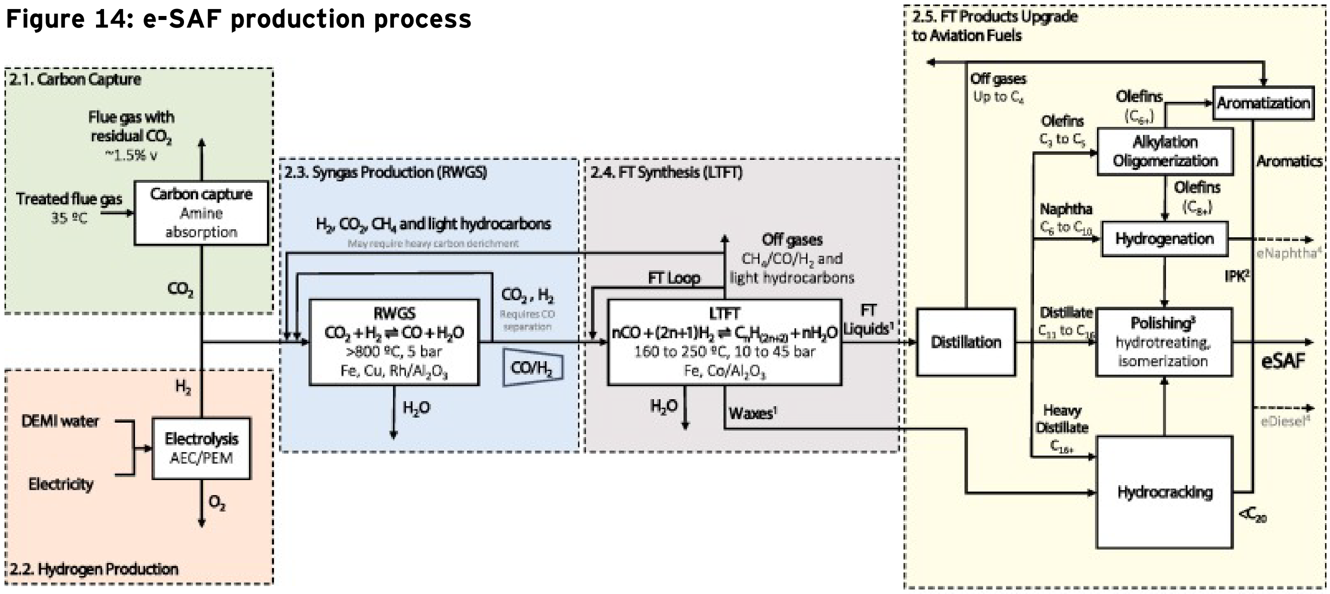
Aviation sector

The aviation sector in India is poised to emerge as a significant consumer of Green Hydrogen as the nation intensifies its decarbonization efforts. With domestic air traffic projected to double by 2030, the pressure on industry to curb emissions is increasing. Green Hydrogen presents a viable low-emission alternative to conventional aviation turbine fuel (ATF), either through direct application in hydrogen fuel cells or as a feedstock for electro-sustainable aviation fuels (e-SAF).

Sustainable aviation fuel (SAF) is produced from renewable or waste-derived feedstocks and serves as a drop-in replacement for conventional jet fuel, offering significant reductions in lifecycle greenhouse gas emissions. There are several certified pathways for SAF production, the most prominent being the HEFA (Hydroprocessed Esters and Fatty Acids) process. In this method, feedstocks like used cooking oil, animal fats, and vegetable oils are hydrotreated using hydrogen under high pressure and temperature. This process removes oxygen from the fatty acids and saturates the molecules, resulting in a hydrocarbon mixture similar to conventional jet fuel. Other production routes include FT-SPK (Fischer-Tropsch Synthetic Paraffinic Kerosene), which uses gasified biomass (such as agricultural residue or municipal solid waste) converted to syngas (a mix of CO and H_2), and then catalytically synthesized into liquid hydrocarbons. Similarly, the alcohol-to-jet (ATJ) pathway involves fermenting biomass into alcohol (like ethanol or butanol), which is then dehydrated, oligomerized, and hydro processed into aviation-grade fuel. All these pathways share the common goal of utilizing renewable carbon sources to produce lower-emission alternatives to fossil-based jet fuels.

On the other hand, electro-sustainable aviation fuel (e-SAF), also known as Power-to-Liquid (PtL) SAF, is a synthetic fuel made using Green Hydrogen and captured carbon dioxide. The production of e-SAF starts with the electrolysis of water using renewable electricity (from solar, wind, etc.) to produce Green Hydrogen. This hydrogen is then combined with CO_2, captured either from industrial sources or directly from the atmosphere (via DAC-Direct Air Capture), through a process known as Fischer-Tropsch synthesis or other catalytic routes. The result is a synthetic hydrocarbon fuel that closely mimics conventional jet fuel in its chemical composition and performance. Unlike bio-based SAF, e-SAF does not rely on land or biomass, making it a more scalable and sustainable option in the long term, especially as renewable electricity becomes more abundant. However, it remains more expensive due to high energy input requirements and current limitations in carbon capture and synthetic fuel synthesis technologies.

Figure 14: e-SAF production process



Source: ScienceDirect (See Ref. No. 65)

In 2023, leading Indian airports such as Delhi and Hyderabad launched pilot flights using SAF to assess its techno-economic feasibility. The government's emphasis on establishing hydrogen hubs near major airports and incorporating aviation in its long-term decarbonization strategy further highlights the sector's potential for Green Hydrogen adoption.

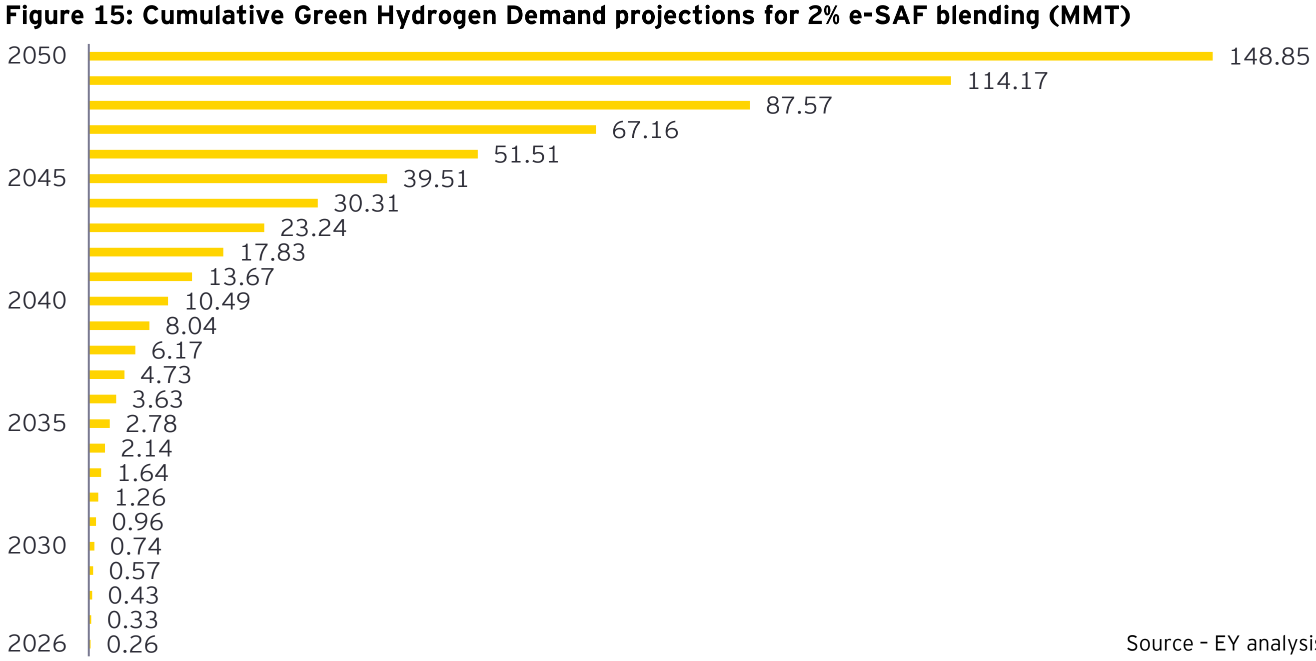
Currently, India relies heavily on ATF derived from crude oil, which is a carbon-intensive fuel. In FY 2023-24, ATF consumption stood at approximately 8.2 MMT. Based on historical consumption trends and the compound annual growth rate (CAGR) of 30%, the projected cumulative consumption of ATF by 2050 is estimated to reach 8,111 MMT.

Recognizing the need for cleaner alternatives, the Government of India approved the blending of up to 2% sustainable aviation fuel (SAF) with ATF in 2023. For e-SAF produced using Green Hydrogen, this 2% blending target translates into a significant opportunity for Green Hydrogen demand of 0.74 MMT by 2030 and 148.85 MMT by 2050. However, it is important to note that blending e-SAF at this level is expected to increase the cost of the blended fuel by approximately 16%, primarily due to the higher production cost of Green Hydrogen and associated fuel synthesis technologies.

Despite this cost challenge, scaling Green Hydrogen adoption in aviation is crucial for aligning with India's net-zero ambitions. Addressing infrastructure gaps, reducing technology costs, and implementing supportive policies will be essential to unlock the full potential of Green Hydrogen in aviation.

The below graph shows the projection of cumulative hydrogen demand for 2% e-SAF in ATF by 2050 in aviation sector in India.

Figure 15: Cumulative Green Hydrogen Demand projections for 2% e-SAF blending (MMT)



Source - EY analysis

Fertilizer sector

India's fertilizer sector is one of the most critical pillars supporting national food security, with nitrogen-based fertilizers like urea playing a central role in enhancing agricultural productivity. The sector is also the largest consumer of industrial hydrogen in the country, primarily used for ammonia synthesis, a precursor for urea and other nitrogenous fertilizers.

The manufacturing process of urea

Ammonia and carbon dioxide are the raw materials for the urea manufacturing process. Usually, urea is manufactured in an ammonia plant because it yields ammonia as a product and carbon dioxide as a byproduct and this carbon dioxide can be recycled directly into the process.

The chemical reactions involved in the process:

The reaction of ammonia and carbon dioxide to form ammonium carbamate.

$2NH_3 + CO_2 \rightarrow NH_2COONH_4$

Decomposition of ammonium carbonate to form urea and water.

$NH_2COONH_4 \rightarrow NH_2CONH_2$ (urea) $+ H_2O$

Note: Both reaction equations above are reversible.

Liquified ammonia is pumped, and compressed carbon dioxide is fed into a reaction chamber. The reactor is the heart of the process, as all the reactions occur within this chamber. The reactor is maintained at a pressure of 14Mpa and a temperature of 170-190°C for the first reaction to take place. The reaction between ammonia and carbon dioxide is highly exothermic. Most of the heat released is utilized in the form of process steam wherever it is needed in to process.

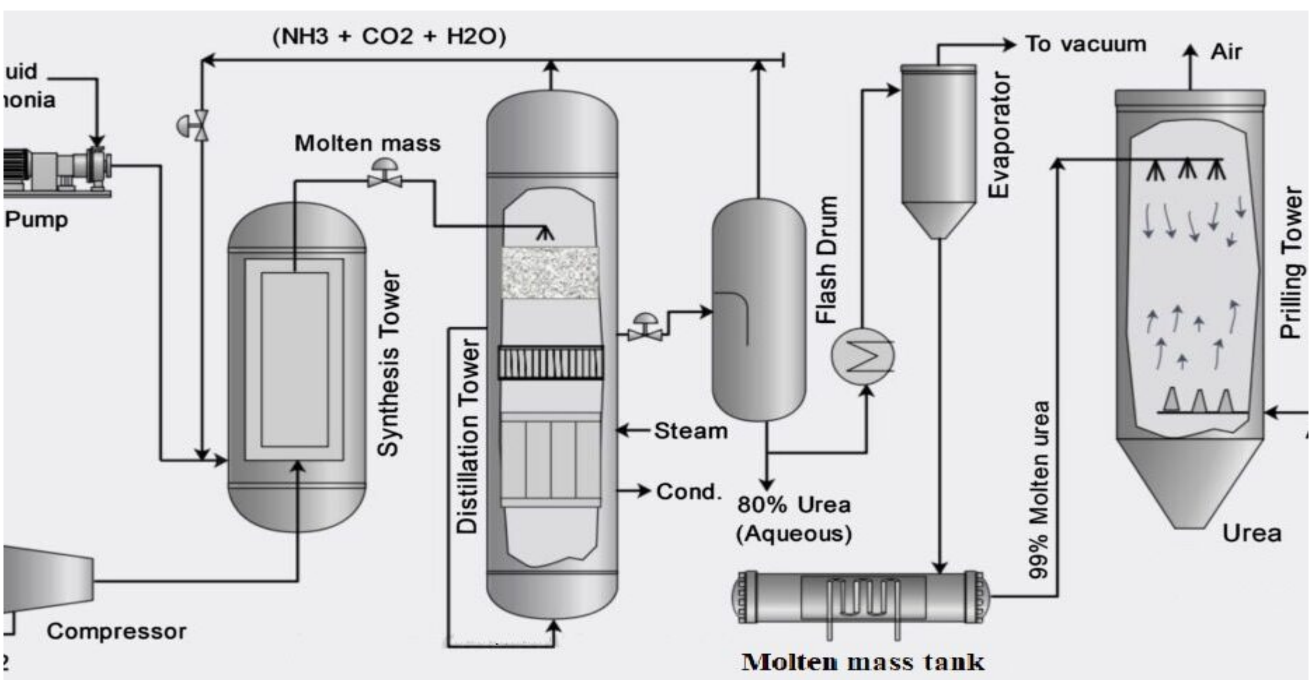
The product from the first reaction flows into a decomposer where the second reaction occurs, and it is an endothermic reaction. It requires a certain energy to begin. Biuret is also formed as a result of decomposition of ammonium carbamate if temperature rise is excessive.

The conversion of the reactants to urea can be increased by increasing the amount of carbon dioxide, if carbon dioxide is present in excess then the conversion can be as high as 85% per pass but optimizing for the proper temperature, pressure and design is a challenge in itself hence usually per pass conversion are kept around 50%. The unreacted materials are recycled, resulting in overall conversion of over 99%. This minimizes the effects on the environment.

The major impurity in urea is water and also unreacted ammonia, carbon dioxide and ammonium carbamate. These are removed using distillation tower and evaporator. The essential condition is to keep the temperature high and pressure low during stages of separation. Under these conditions, ammonium carbamate will decompose back into ammonia and carbon dioxide, and some carbon dioxide and ammonia will also flash off. The primary process occurring in the evaporator is concentration. During this concentration process, the optimum temperature should be maintained so that the urea remains in a molten state and crystals are not formed inside the evaporator.

The molten urea is passed through nozzles inside the prilling tower. Compressed air is passed in the tower so that its flow is counter-current with respect to that of molten urea. The urea gets solidified in the prilling tower, and air helps in shaping it in the form of prills or granules. The urea is then stored and ready to be sold.

Figure 16: Urea production process



Source: EBL Engineering Ltd (See Ref. No. 50)

At present, the used hydrogen is produced through fossil fuel-based processes, such as steam methane reforming (SMR) and naphtha reforming, making the sector a significant source of carbon emissions.

Transitioning to Green Hydrogen presents an opportunity to decarbonize fertilizer production while enhancing India's energy self-reliance and climate resilience. In the way of significant initiative, the Government of India allocated 7,24,000 MMT for use of green ammonia in fertilizer sector under the National Green Hydrogen Mission.

From a techno-economic perspective, co-locating Green Hydrogen production near fertilizer manufacturing hubs makes logistical and financial sense, given the continuous and high-volume nature of hydrogen usage in ammonia synthesis. The shift to Green Hydrogen also aligns with India's broader goals of achieving energy self-reliance, reducing import dependence on natural gas (especially in light of volatile LNG prices), and meeting its climate commitments under the Paris Agreement.

However, the transition is not without challenges. The cost of Green Hydrogen is currently higher than grey hydrogen, largely due to the capital cost of electrolyzers and the intermittency of renewable energy. To address this, the government is offering incentives through the Strategic Interventions for Green Hydrogen Transition (SIGHT) program, which includes support for both electrolyzer manufacturing and Green Hydrogen production. Long-term demand certainty, stable policy frameworks, and infrastructure development (such as renewable power supply and water access for electrolysis) will be critical to unlocking large-scale adoption.

Fertilizer demand and hydrogen utilization

The overall demand for fertilizers in India has steadily grown over the past three financial years, increasing from 54 MMT in FY 2021-22 to 59.9 MMT in FY 2023-24, a total average growth rate of 4.74%. Among the key products:

Urea remains dominant, with an average demand of 36.2 MMT, increasing by 6% over the past three years.

DAP (Di-ammonium Phosphate) and NPK (Nitrogen, Phosphorus, Potassium) fertilizers had relatively stable demand, averaging 10.4 MMT and 11.2 MMT, respectively.

Hydrogen is primarily required for ammonia production in urea synthesis. Based on sectoral analysis:

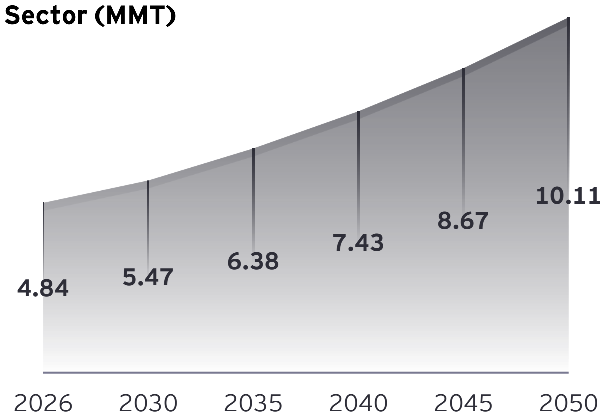
> Urea contributes to 20.66 MMT of ammonia demand, requiring 3.68 MMT of hydrogen.
>
> DAP and NPK collectively add 0.73 MMT of hydrogen demand.

This brings the total current hydrogen requirement for the fertilizer sector to approximately 4.41 MMT per annum.

Hydrogen demand projection till 2050

Assuming a 4.74% compound annual growth rate (CAGR) in hydrogen demand, aligned with the historical trend in fertilizer consumption, the hydrogen requirement is projected to grow steadily over the coming decades.

Figure 17: Cumulative H2 Demand in Fertilizer Sector (MMT)



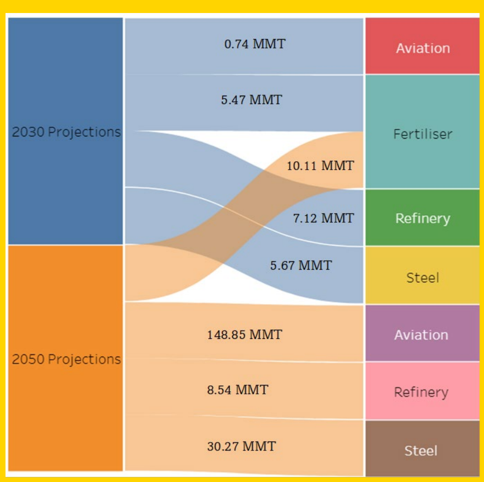
Source - EY analysis

By 2050, the annual hydrogen demand in the fertilizer sector is expected to more than double, reaching 10.11 MMT, driven by increasing agricultural productivity requirements, population growth, and rising food grain targets.

Summary

Hydrogen demand in India is projected to rise significantly across key sectors between 2030 and 2050, in line with the nation's transition to a low-carbon economy. In 2030, the estimated demand is distributed among fertilizers (5.47 MMT), refineries (7.12 MMT), steel (5.67 MMT), and aviation (0.74 MMT). By 2050, a major shift is anticipated, particularly in the aviation sector, where demand is expected to surge to 148.85 MMT- making it the largest hydrogen-consuming sector, assuming a 2% Green Hydrogen blending mandate is maintained through 2050. The steel sector is also projected to see a sharp increase in demand, reaching 30.27 MMT, driven by decarbonization efforts in heavy industry. Refinery demand is expected to grow modestly to 8.54 MMT, while fertilizer sector demand is projected to nearly double, rising to 10.11 MMT by 2050.

Figure 18: 2030 and 2050 projections of hydrogen demand in different sectors



Source - EY analysis

6

Regulatory provisions governing Green Hydrogen in India

The Manufacture, Storage, and Import of Hazardous Chemical (MSIHC) Rules, 1989; Environment (Protection) Act, 1986

Hydrogen is classified as a hazardous chemical under the provisions of the Manufacture, Storage and Import of Hazardous Chemicals (MSIHC) Rules, 1989. The regulatory framework is as follows:

Schedule 5 of the Rules outlines the designated authorities responsible for executing specific regulatory functions.

The Central Pollution Control Board (CPCB), State Pollution Control Boards (SPCBs), or Committees constituted under the Environment (Protection) Act, 1986, as applicable, are the competent authorities for the following functions:

- Grant of approvals as per ***Rule 7***
- Receipt and assessment of safety reports under ***Rule 10***
- Supervision of formulation and execution of on-site emergency plans under ***Rule 13***

These authorities are responsible for regulatory oversight of hazardous chemicals, including hydrogen.

The MSIHC Rules, 1989—formulated under the Environment (Protection) Act, 1986—provide a regulatory framework to ensure safe handling, storage, and import of hazardous chemicals in India. The Ministry of Environment, Forest and Climate Change (MoEFCC) is the nodal Ministry responsible for implementation.

Entities engaged in the manufacture or import of hazardous chemicals, including hydrogen, are required to obtain prior authorization from the competent authority. The application must include comprehensive details on the nature of the chemical, manufacturing or importation processes, storage infrastructure, and safety mechanisms deployed.

The Rules prescribe stringent norms for the storage and handling of hazardous substances, which include:

- Maintenance of separate, well-ventilated, and secure storage areas
- Proper labeling and marking of chemical containers
- Provision of adequate safety equipment and personal protective gear
- Periodic safety audits and upkeep of relevant records.

MoEFCC, vide OM dated 28 July 2023, clarified that standalone Green Hydrogen or green ammonia plants using electrolysis powered by renewable energy do not require prior environmental clearance under the EIA Notification, 2006. However, consents under the Air Act, 1981 and Water Act, 1974, along with other applicable statutory clearances, must be obtained. If such plants are located within an existing unit requiring prior EC, the hydrogen or ammonia component must be added through an amendment to the existing EC.

Petroleum and Explosives Safety Organization (PESO): Static and Mobile Pressure Vessels (Unfired) Rules 2016; Gas Cylinders Rules, 2016

The Petroleum and Explosives Safety Organisation (PESO), formerly known as the Department of Explosives, functions as the nodal agency for the regulation of hazardous substances, including explosives, compressed gases, and petroleum products. Since its establishment, PESO has been entrusted with ensuring public safety in relation to such materials.

Static and Mobile Pressure Vessels (Unfired) Rules 2016 (SMPV(U))

The SMPV(U) Rules, 2016, notified by PESO, regulate the design, fabrication, testing, import, installation, operation, and maintenance of unfired pressure vessels in India. These rules apply to a range of industrial vessels, including storage tanks, reactors, piping systems, and cylinders, used under varying pressures and capacities. The objective is to prevent accidents such as leaks or explosions, through prescribed safety standards.

Key regulatory provisions under the Rules include: Mandatory licensing by PESO for all manufacturers, importers, and installers of pressure vessels

Compliance with specified norms for material selection, design parameters, and construction methods

Compulsory testing and inspection before commissioning and at defined intervals during the operational life of the equipment

Prescribed procedures for operational safety, maintenance, and repairs

Emphasis on minimizing risks to personnel, property, and public safety

Contribution to a structured regulatory environment for the safe management of pressure vessels

Rule 45–License for storage of compressed gas: No person shall store any compressed gas in any vessel except under and in accordance with a license granted under these Rules by the Chief Controller or a Controller authorized by him

Rule 46–Prior approval of specification and plans:

- Specifications and layout plans of the proposed vessels and premises, drawn to scale in triplicate
- Clearly demarcated areas to be licensed, in accordance with the provisions of the Rules

Rule 48–License for transport of compressed gas: No compressed gas filled in a vessel shall be transported by a vehicle unless under and in accordance with a license granted under these Rules. The provisions of this Rule do not apply to transport by railway administration

Rule 50–Application for license: An applicant seeking a license under these Rules shall submit:

- Form AS-1 for storage (Form LS-1A), Form AS-2 for transport (Form LS-2);
- Safety certificate under Rule 33 or Rule 43, as applicable;
- Test and inspection certificate as per Rule 13(2);
- Four sets of drawings for site layout and installation or mounting plans;
- License fee as specified in Schedule I;
- No Objection Certificate from the District Authority (in case of storage);
- Vehicle registration certificate and weighment slip (for mobile vessels).

Gas Cylinders Rules, 2016

Notified under the Explosives Act, 1884, the Gas Cylinders Rules, 2016 provide a regulatory framework for the manufacture, filling, possession, storage, and transportation of compressed gas cylinders, including hydrogen. These rules are implemented by PESO under the administrative control of the Department for Promotion of Industry and Internal Trade (DPIIT), Ministry of Commerce and Industry.

The Gas Cylinders Rules, 2016, notified by PESO, serve as a critical regulatory instrument to facilitate the safe handling of gas cylinders across the country. These rules have been framed with the objective of minimizing the risk of accidents and injuries arising from cylinder failures, thereby safeguarding workers and the general public from associated hazards. The framework promotes adherence to safe practices in the design, manufacturing, storage, transportation, and usage of gas cylinders and facilitates alignment with international safety benchmarks, contributing to enhanced industrial competitiveness. The rules comprehensively cover the following key aspects:

Manufacture: Prescribe specifications relating to materials, design norms, manufacturing procedures, and requisite safety features applicable to various categories of gas cylinders.

Storage: Lay down conditions for the proper storage of cylinders, including the nature and location of storage facilities, along with mandatory safety provisions.

Transportation: Define standards for the safe transport of gas cylinders, including requirements pertaining to transport vehicles, loading or unloading protocols, and precautionary measures.

Use: Establish operational guidelines for end-use, covering operator training, safety protocols, and periodic maintenance procedures.

Rule 2(xvi): Defines gas cylinders as closed metal containers ranging from 500 ml to 1000 liters in capacity.

Rule 2(ix): Recognizes hydrogen as part of the definition of Compressed Natural Gas (CNG), when mixed with methane.

Rule 3: Lays down general prohibitions on handling and transport without proper authorization.

Rules 4 to 17: Prescribe technical and safety requirements covering cylinder specifications, approval processes, manufacturer markings, and material standards.

Rule 22: Mandates that all electrical fittings in filling premises be flameproof and conform to IS/IEC 60079.

Rules 35 and 36: Provide for periodic hydrostatic testing, with strict condemnation protocols for unfit or overaged cylinders.

Rule 45 and 47: Prohibit filling or licensing of premises without prior approvals, certifications, and adherence to notified standards.

Schedule IV: Details infrastructure and safety systems required for authorized cylinder testing stations.

Gas Cylinders (Amendment) Rules, 2025 – Provisions relating to hydrogen

The Gas Cylinders (Amendment) Rules, 2025, notified via G.S.R. 225(E), dated 11 April 2025, introduce a comprehensive regulatory framework for compressed hydrogen gas (CHG), including safety, storage, testing, and dispensing provisions. The amendments are applicable under the Explosives Act, 1884 and amend the principal Gas Cylinders Rules, 2016.

Definitions introduced (in Rule 2 of the Gas Cylinders Rules, 2016)

- **Compressed Hydrogen Gas:** Hydrogen, including Green Hydrogen, compressed and intended to be used as automotive fuel conforming to IS 16061 or ISO 14687.
- **Hydrogen Gas Storage System:** A closed system used for retaining hydrogen in gaseous or liquid form upstream of the source valve and includes cylinder or gas cylinder cascade.
- **Compressed Hydrogen Gas Mother Station:** A facility connected to a hydrogen gas pipeline or onsite hydrogen generation system (through an electrolyser or reformer), equipped with a compressor for filling mobile cascades used by daughter stations, and including stationary cascades for dispensing compressed hydrogen gas to vehicles.
- **Compressed Hydrogen Gas Daughter Station:** Refers to a facility that is not connected to a hydrogen gas pipeline and receives compressed hydrogen gas via mobile cascades for further dispensing.
- **Compressed Hydrogen Gas Daughter Booster Station:** Refers to a facility not connected to a hydrogen gas pipeline, where mobile or stationary cascades are connected to a booster compressor to elevate discharge pressure for vehicle refueling.
- **Compressed Hydrogen Gas Online Station:** Refers to a facility connected to a hydrogen gas pipeline or featuring onsite hydrogen generation via an electrolyser or reformer, and equipped with a compressor for filling stationary cascades used for dispensing hydrogen gas to vehicles.

Rules 4 and 5: Cylinder and relief valve standards

- **Rule 4(1):** Cylinders intended for compressed hydrogen gas must conform to standards such as CGA S-1.1, CGA S-1.2, CGA S-1.3, R-134, or other standards notified in Schedule I.
- **Rule 5(1A):** Safety relief devices or pressure relief devices used in CHG cylinders shall conform to IS 5903 or equivalent international standards.

Rule 6: Markings on cylinders (barcode requirements and restrictions on cylinder filling)

- Barcode marking requirement: Every cylinder and cryogenic container intended for filling with compressed hydrogen gas, auto LPG, CNG, bio-CNG, or any other specified gas shall be affixed with a permanent and tamper-proof barcode, positioned at a conspicuous location on the body of the cylinder or container. The barcode shall function as an electronic identification number in the form of a QR code, RFID, or any other electronically scannable code.
- Compliance timelines for existing cylinders: In respect of cylinders and containers manufactured prior to the date of commencement of these Rules, compliance with the barcoding requirement shall be ensured within 365 days from the date of notification.
- Submission of barcode data upon notice: Any person engaged in the manufacture, import, possession, filling, transport, or use of such cylinders or containers shall, upon issuance of a written notice by the inspecting authority, submit the barcode identification details in both digital and physical format within 48 hours or such time as may be stipulated in the said notice.
- Prohibition on filling of non-compliant cylinders: No compressed hydrogen gas or other notified gas shall be filled into any cylinder or cryogenic container unless, the cylinder bears a valid barcode affixed in the prescribed manner; the cylinder has undergone periodic testing at a testing station duly recognized by the Chief Controller; the cylinder has been approved for use under these Rules.

Rule 22 (electrical installations): As per substituted Rule 22, all electrical components used in premises for hydrogen generation, compression, storage, transfer, and dispensing shall meet the following requirements:

- All electrical fittings (including meters, distribution boards, switches, lamps, motors, etc.) shall conform to IS/IEC 60079 series or other standards as approved by the Chief Controller.
- Electrical components in hydrogen-related systems—whether bulk or non-bulk compressed hydrogen gas systems, hydrogen generation units, compressors, or dispensers—shall comply with standards accepted by the Chief Controller.
- All such components shall be equi-potentially bonded and grounded, and electrical continuity shall be ensured to prevent electrostatic charge accumulation in hydrogen-handling premises.

Rules 35 (periodicity of examination and testing of cylinders): Onboard compressed hydrogen gas cylinders shall be subjected to hydrostatic or hydrostatic stretch testing and other tests under Schedule IV once every three years.

Rule 36 (condemning of cylinder):

- The maximum service life of onboard compressed hydrogen gas (CGH) cylinders shall be 15 years.
- For cascade-mounted CHG cylinders, the maximum service life shall be 20 years.
- Cylinders failing periodic tests or exceeding their service life shall be condemned and destroyed as per ISO 11623, using mechanical crushing into irregular pieces.

Licensing requirements for compressed hydrogen gas (CHG): Dispensing stations (Rule 47 and Form H) in accordance with Rule 47(1) of the Gas Cylinders Rules, 2016, as amended by the Gas Cylinders (Amendment) Rules, 2025, every application for the grant of a license for a CHG dispensing station shall be accompanied by the following documents and technical particulars:

- **Site and layout documentation:**
  - A detailed layout plan of the premises and surrounding area covering a 500-meter radius from the facility boundary;
  - Sectional elevation views of all equipment, including the hydrogen generation system, storage vessels, valves, pumps, dispensers, and fire-fighting infrastructure;
- **Safety and risk documentation:**
  - A Hazard and Operability (HAZOP) Study in accordance with IEC 61882, prepared by a recognized engineering firm, along with close-out reports;
  - An Emergency Response Plan (ERP) in compliance with ISO 14001, prepared by an agency authorized by the central government.
- **Process and control systems:**
  - Piping and Instrumentation Diagrams (P&ID) for all vessels, compressors, dispensers, and associated infrastructure;
  - Description of safety interlock systems integrated with hydrogen leak detection mechanisms.

The [Oilfields] (Regulation and Development) Act, 2025

The Oilfields (Regulation and Development) Amendment Act, 2025 (Act No. 6 of 2025), notified on 28 March 2025, revises the definition of "mineral oils" under Section 3(c) to include various forms of hydrocarbons. Hydrogen is not included in this revised definition and is therefore not eligible for licensing under the exploration and production framework of the principal Act.

However, the amendment introduces Section 6A(o), which empowers the government to promote decarbonization measures, including:

"Promote and facilitate adoption of measures for reducing carbon and greenhouse gas emissions and decarbonizing operations including but not limited to use of oilfields for other purposes, such as, production of hydrogen, carbon capture utilization and storage or coal gasification."

Accordingly, the Act now enables the use of oilfield sites and infrastructure for hydrogen production as part of recognized decarbonization activities.

Ministry of Road Transport and Highways (MoRTH

- Hydrogen is notified on 16 September 2016, as an automotive fuel vide GSR 889 (E) for BS-VI vehicles enforced from 1 April 2020.
- GSR 579(E) dated 23 September 2020 has notified safety norms regarding hydrogen fuel cell vehicles and its components.
- GSR 585(E) dated 25 September 2020 has notified safety norms regarding hydrogen-CNG blend ICE vehicles and its components (18% blend of hydrogen with CNG (HCNG)).
- GSR 683(E) dated 6 September 2022 has notified safety norms regarding hydrogen ICE vehicles and its components.
- MoRTH vide notification, GSR 885(E) dated 16 December 2022, has indicated the specifications of hydrogen as a reference fuel for ICE BS IV vehicles.
- MoRTH, vide G.S.R. 746(E) dated 16 October 2023, notified Rule 125M under CMVR, 1989, specifying type approval for hydrogen-fueled M and N category ICE vehicles as per AIS 195:2023, and fuel specifications as per IS 16061:2021, until BIS standards are notified.
- As part of the NGHM, MoRTH approved five projects involving a total of 37 vehicles—15 hydrogen fuel cell-based and 22 hydrogen internal combustion engine-based—and nine hydrogen refueling stations (pilot projects).

The Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016

The Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 have been notified to ensure the safe handling, generation, processing, treatment, packaging, storage, transportation, use, reprocessing, collection, conversion, sale, destruction, and disposal of hazardous waste.

As per Rule 3(1)(21), the occupier of any factory or premises is responsible for the environmentally sound management of hazardous and other waste. This includes obtaining prior authorization from the concerned State Pollution Control Board (SPCB) or Pollution Control Committee (PCC) for activities involving waste management.

The occupier is required to comply with the conditions specified in the authorization and adhere to the provisions of the Rules. Additional obligations include maintenance of records, submission of annual returns, and compliance with applicable regulations governing import, export, recycling, recovery, reuse, or utilization of hazardous wastes.

Table 2: Overview of regulations governing Green Hydrogen in India

Segment of value chain	Category	Responsible authority	Applicable regulation/description
Production	Green Hydrogen generation	Ministry of New and Renewable Energy (MNRE)	MNRE, after extensive consultations with stakeholders, has established that Green Hydrogen shall be characterized by a maximum well-to-gate emission of 2 kg CO_2 equivalent per kg of hydrogen. This includes emissions from water treatment, electrolysis, purification, drying, and compression processes.
	Safety standards	Ministry of Environment, Forest and Climate Change (MoEFCC) (Department of Environment, Forests and Wildlife)	Governed under the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989, to ensure safety during production.
	Waste management	Central Pollution Control Board (CPCB)	Covered by the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016, address disposal and handling of waste by-products.
	Environmental emissions	Central Pollution Control Board (CPCB)	Regulated through the Air (Prevention and Control of Pollution) Act, 1981, for monitoring emissions.
Storage	Storage infrastructure	Petroleum and Explosives Safety Organization (PESO)	Regulated under the Static and Mobile Pressure Vessels (Unfired) Rules, 2016 and its subsequent amendments, covering design and operational safety.
	Chemical safety	MoEFCC, Department of Environment, Forests and Wildlife	Subject to the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989 for chemical safety in storage.
Transportation	General transport of hydrogen	Petroleum and Explosives Safety Organization (PESO)	Covered by the Static and Mobile Pressure Vessels (Unfired) Rules, 2016, and its subsequent amendments for mobile storage and handling.
	Cylinder-based transport	Petroleum and Explosives Safety Organization (PESO)	Regulated under the Gas Cylinder Rules, 2016, and its subsequent amendments; specific to hydrogen transport via cylinders.
End use	Import regulations	MoEFCC, Department of Environment, Forests and Wildlife	Imports governed by the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989, ensuring safe import practices.
	Fuel cell electric vehicles (FCEVs)	Ministry of Road Transport and Highways (MoRTH)	Subject to Automotive Industry Standards and associated technical protocols for vehicle safety and performance.

Table 3: Summary of hydrogen-related regulations: India and international jurisdictions

S. No.	Value chain segment	India	United States of America	United Kingdom	Australia
1	Production	The Ministry of New and Renewable Energy has defined Green Hydrogen as hydrogen with a well-to-gate emission of not more than 2 kg of carbon dioxide equivalent per kg of hydrogen, inclusive of water treatment, electrolysis, purification, drying, and compression. The Ministry of Environment, Forest and Climate Change regulates safety under the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989. The Central Pollution Control Board administers the Air (Prevention and Control of Pollution) Act, 1981 and the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 for emissions and waste disposal.	The Environmental Protection Agency regulates environmental and greenhouse gas emission compliance. The Department of Energy is responsible for establishing standards for clean hydrogen production.	The Planning (Hazardous Substances) Regulations,2015 govern the safe handling of hazardous materials. The Dangerous Substances and Explosive Atmospheres Regulations, 2002 address workplace safety. The Office of Gas and Electricity Markets and the Environment Agency regulate safety, electricity markets, and health requirements.	Dangerous Goods Safety (Storage and Handling) Regulations, 2007 and the Work Health and Safety Act, 2011 govern safety and workplace handling. The Recycling and Waste Reduction Act, 2020 and the National Greenhouse and Energy Reporting Act, 2007 address waste and emissions. The Industrial Chemicals Act, 2019 and the Australian Energy Market Act, 2004 govern chemical regulation and energy markets.

S. No.	Value chain segment	India	United States of America	United Kingdom	Australia
2	Storage	Regulated under the Static and Mobile Pressure Vessels (Unfired) Rules, 2016 notified by the Petroleum and Explosives Safety Organisation. The Ministry of Environment, Forest and Climate Change governs storage safety and container labelling under the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989.	The Federal Energy Regulatory Commission grants authorization for underground hydrogen storage. The Occupational Safety and Health Administration oversees workplace safety compliance for hazardous material storage.	Storage of hazardous substances is governed by the Planning (Hazardous Substances) Regulations, 2015 and the Control of Major Accident Hazards Regulations. The Dangerous Substances and Explosive Atmospheres Regulations address explosive risk. Storage facility operations require permits from the Environment Agency.	Governed under the Gas Supply (Safety and Network Management) Regulation, 2022. Definition of gas, each of the following is declared to be a gas: (a) Hydrogen gas that is not mixed with another gas. (b) A mixture of hydrogen gas and either natural gas or liquefied petroleum gas.
3	Transportation	The Petroleum and Explosives Safety Organisation (PESO) regulates the transportation of hydrogen through the Static and Mobile Pressure Vessels (Unfired) Rules, 2016, which specify design and safety requirements for transport vessels. The Gas Cylinder Rules, 2016, also notified by PESO, provide for the safe transportation of hydrogen in cylinders. The Ministry of Environment, Forest and Climate Change governs the import of hazardous chemicals, including hydrogen, under the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989. The Petroleum and Natural Gas Regulatory Board (PNGRB) oversees the natural gas pipeline infrastructure. While hydrogen is not currently within its formal mandate, discussions are underway to consider its inclusion.	The Bureau of Safety and Environmental Enforcement governs transportation infrastructure on the Outer Continental Shelf. The Federal Energy Regulatory Commission regulates import and export terminals for hydrogen and associated transport systems. The Pipeline and Hazardous Materials Safety Administration prescribes minimum safety standards for the transport of hazardous materials, including hydrogen. The United States Coast Guard regulates shore-to-vessel and vessel-to-shore transfer operations involving hazardous materials. Regulations are also in place for hydrogen transportation by rail, road, and inland waterways.	Hydrogen transportation is governed by multiple regulations, including the Pipelines Safety Regulations, 1996, which specify pipeline design requirements. The Gas Safety (Management) Regulations, 1996 govern the percentage of hydrogen that may be blended with natural gas. The Dangerous Substances and Explosive Atmospheres Regulations mandate businesses to conduct risk assessments for the transportation of dangerous substances, including hydrogen. Separate regulations are applicable for transportation via road, rail, and inland waterways.	The Petroleum and Gas (Production and Safety) Act, 2004 prescribes technical standards for the design and safe operation of hydrogen pipelines. The National Transport Commission's Australian Code for the Transport of Dangerous Goods by Road and Rail provides a comprehensive regulatory framework for road and rail transport of hydrogen. Maritime transport is governed under the Protection of the Sea (Prevention of Pollution from Ships) Act, 1983, administered by the Australian Maritime Safety Authority.

S. No.	Value chain segment	India	United States of America	United Kingdom	Australia
4	End usage	End-use of hydrogen is regulated by multiple authorities. The Ministry of Environment, Forest and Climate Change governs aspects of hazardous chemical usage under the Manufacture, Storage and Import of Hazardous Chemical Rules, 1989. The Petroleum and Explosives Safety Organisation regulates safety for hydrogen storage and dispensing through the Gas Cylinder Rules, 2016. The Ministry of Road Transport and Highways prescribes Automotive Industry Standards for hydrogen Fuel Cell Electric Vehicles (FCEVs). Technical standards for stationary, and industrial end-use applications are under development.	Sector-specific regulations apply to hydrogen used in electricity generation, backup and auxiliary power systems, industrial and chemical processing, and fuel cell vehicles. Separate frameworks exist for use as fuel and for storage and refueling infrastructure.	Regulatory provisions exist across sectors, including electricity production, industrial processing, hydrogen blending, and use in FCEVs. The regulatory framework also covers hydrogen refueling infrastructure and export-import mechanisms.	Australia has defined frameworks for hydrogen usage across electricity, mobility, and export sectors. Regulations apply to the production and utilization of hydrogen in stationary and mobile applications, including FCEVs, refueling infrastructure, and terminals for export-import purposes.

7

Recommendations for enhancing Green Hydrogen offtake in India

India has made significant strides from intention to action regarding Green Hydrogen (GH_2) offtake. In the refining sector, landmark tenders have identified a narrow price range, excluding GST, between INR328 and INR336/kg, with HPCL in Visakhapatnam at INR328/kg (ex-GST) and IOCL in Panipat at INR397/kg, including 18% GST (₹336/kg ex-GST). This establishes a credible benchmark for the bankable substitution of Grey Hydrogen in processing units. In the fertilizers sector, the first Green Ammonia auction by Solar Energy Corporation of India (SECI) has revealed a price of INR55.75/kg on a 10-year contract, supported by an intermediary Payment Security Mechanism (PSM), with subsequent results ranging from INR51.8 to INR52.25/kg. Coupled with the MNRE Green Hydrogen Standard ($\leq$2 kg CO_2e/kg H_2), Green Energy Open Access (GEOA), Inter-State Transmission System (ISTS) charge waivers, evolving PNGRB codes for blending and pipelines, and Harit Sagar port guidelines (ammonia bunkering by 2035), there exists a robust policy framework to scale domestic demand.

As there are various stakeholders in the development of a sustainable and scalable hydrogen economy, it is important to highlight the interdependent relationship between government initiatives, industrial investments, and technological advancements. These recommendations seek to address the key economic and infrastructural challenges that hinder hydrogen adoption.

1 Aligning policies to support Green Hydrogen transition

- **Enhancing hydrogen procurement obligations:** Establishing regulatory policies that encourage industrial sectors to procure a defined percentage of their total energy consumption from green hydrogen. This will create predictable and sustained demand, thereby incentivizing investments in Green Hydrogen production and infrastructure
- **Phasing out incentives for carbon-intensive energy sources:** Systematically reallocating existing subsidies and financial support away from fossil fuels and other high-emission energy technologies, directing these resources towards renewable energy initiatives. Additionally, implementing a comprehensive carbon pricing mechanism, such as a carbon tax, can be considered to internalize the environmental costs of carbon emissions. This could enhance the economic viability of Green Hydrogen by creating a more level playing field relative to conventional, carbon-intensive alternatives.

2 Institutionalizing Rolling Demand Aggregation with PSM

The initial refinery and fertilizer tenders have demonstrated that structured demand aggregation, supported by a Payment Security Mechanism, can yield competitive prices and bankable offtake contracts. This approach could evolve into a recurring, pragmatic process rather than a series of isolated transactions.

Owing to the decarbonisation initiatives of the marine sector, global marine fuel is a big export potential from green hydrogen producers.

- **Refineries:** Conducting semi-annual Green Hydrogen offtake rounds for refineries, led by a centralized procurer using standardized Green Hydrogen Purchase Agreements (GHPAs) with tenors of up to 25 years, incorporating explicit indexation for power tariffs, foreign exchange, and CPI/WPI. The target is to secure 0.6 to 0.8 MTPA of Green Hydrogen equivalent by FY2030.
- **Fertilizers (Green Ammonia):** Continuing the Mode-2A program as a rolling initiative through further tranches with long-term (25 years) contract durations following the price discovery under the current tender for 724,000 TPA, aiming for a minimum of 0.8 MTPA of Green Hydrogen equivalent allocated under NGHM.
- **Green Methanol:** International regulatory developments are accelerating the adoption of Green Methanol. The International Maritime Organization (IMO) has revised its greenhouse gas strategy, mandating a minimum 40% reduction in carbon intensity across international shipping by 2030 (compared to 2008 levels), with additional targets of a 20% reduction in total GHG emissions by 2030 and 70% by 2040, progressing toward net-zero emissions by around 2050. The IMO Marine Environment Protection Committee (MEPC 83) has approved the binding Net-Zero Framework, set to come into force between 2027 and 2028, establishing global emissions intensity standards and a mandatory carbon pricing mechanism for vessels over 5,000 gross tonnage, which emit 85% of total CO2 emissions from international shipping.

  Compelled by IMO targets, the shipping industry is transitioning to Green Methanol and Green Ammonia-powered vessels. Marine engine manufacturer MAN Energy Solutions has, for instance, developed methanol-capable dual-fuel engines (ME-LGIM series), with the first retrofitted ships expected to enter commercial operation by 2026. Concurrently, many shipping companies have announced the deployment of methanol-powered vessels commencing in 2026. Global industry assessments suggest that the annual demand for Green Methanol could reach approximately 550 to 600 million tons if the entire global shipping fleet transitions to methanol-based propulsion.

3 Green Hydrogen Adoption Roadmap for Industrial Sector

The Green Hydrogen and Derivatives Consumption Obligation would establish a legally binding floor for domestic demand, providing investors and developers with long-term visibility. It could:

- Be designed as a tradable compliance mechanism, allowing obligated entities to purchase compliance certificates if unable to meet their own targets physically.
- Include provisions for banking and rollover of surplus certificates to incentivize early adoption.
- Increase the share of Green Ammonia to 30%-40% in total ammonia feedstock by FY2030.

4 Operationalizing a National Registry and Certification System

While the Green Hydrogen Standard of India has been notified, its implementation requires an operational national registry to provide traceability and marketable attributes. This registry could:

- Issue digital attribute certificates for each kilogram of green hydrogen or derivatives, containing origin, production date, renewable energy source, and carbon intensity data.
- Align with the Green Hydrogen standard (≤2 kg) of carbon dioxide equivalent per kilogram of hydrogen) for domestic use and be adaptable to stricter international standards.
- Support monthly time correlation for domestic consumption in the initial years and be capable of hourly matching for export parcels by 1 January 2030, to comply with the European Union Renewable Fuels of Non-Biological Origin Delegated Act.
- Enable certificate transferability to support compliance trading for the Green Hydrogen and Derivatives Consumption Obligation and voluntary markets.
- Harmonisation of Indian Standards with global standards.

5 Scaling Hydrogen Hubs, Valleys, and port bunkering

Scaling Hydrogen Hubs, Valleys, and port bunkering is a critical strategy for decarbonizing hard-to-abate sectors such as shipping, heavy industry, and long-haul transport. The NGHM supports the creation of Valleys and Hubs at ports and other prominent locations, but this should be expanded beyond pilot scales. A comprehensive framework is needed to commercialize these developments and scale them for production and utilization.

It is essential to provide common-user storage infrastructure that allows multiple offtakers to access shared facilities, thereby reducing costs and enabling economies of scale. Concurrently, establishing accredited laboratories at hub locations would ensure reliable hydrogen purity verification and lifecycle emissions testing, which are critical for compliance, safety, and certification of low-carbon fuels.

6 Moving City Gas Distribution blending from pilots to routine operation

Hydrogen blending in City Gas Distribution (CGD) networks presents an immediate, scalable pathway for low-volume offtake and introduces the public to Green Hydrogen usage. To transition from pilot trials to routine operation, it is essential to finalize and notify a national technical code and safety protocol permitting routine blending of 10%-15% by volume. To incentivize adoption, the government could introduce tradable blending certificates, enabling CGD licensees who exceed blending obligations to monetize surplus blending by selling certificates to entities unable to meet their targets.

7 Mitigating offtaker creditworthiness risks

Many potential offtakers in the hydrogen value chain—particularly small and medium enterprises (SMEs), municipal bodies, or early adopters in emerging sectors and developing economies—often lack investment-grade credit ratings, significantly impacting project bankability and deterring private investment. To address this, governments and financial institutions could deploy targeted credit support instruments, such as guarantees, political risk insurance, or standby letters of credit through public sector banks or guarantee funds, to enhance the creditworthiness of these offtakers. Blended finance mechanisms could also be leveraged, using concessional capital to co-finance projects involving lower-rated counterparties, thereby attracting private capital and lowering the overall cost of financing. Additionally, offtaker due diligence support—including technical assistance, credit assessment frameworks, and standardized contracting templates—could be made available to help less established entities build credibility and participate effectively in the hydrogen market.

Conclusion

The success of the hydrogen economy hinges on multisectoral collaboration. The governments must establish robust regulatory frameworks, fiscal incentives, and foundational infrastructure. Industry participation, from startups to multinational corporations, is essential to drive innovation, capital deployment, and market expansion. Researchers play a critical role in advancing the technology and knowledge essential for sustainable hydrogen solutions.

This integrated framework provides a clear pathway for a hydrogen-powered future that aligns with India's climate goals, enhances industrial competitiveness, and strengthens energy security. These recommendations help stakeholders in their effort to collectively foster a thriving hydrogen economy that supports sustainable development and addresses pressing environmental challenges.

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Glossary

AS	Additional Surcharge
ATF	Aviation Turbine Fuel
ATJ	Alcohol-to-Jet
BIS	Bureau of Indian Standards
BESS	Battery Energy Storage Systems
BF-BOF	Blast Furnace-Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CSS	Cross-Subsidy Surcharge
CNG	Compressed Natural Gas
CRU	Catalytic Reforming Unit
CAGR	Compound Annual Growth Rate
CPCB	Central Pollution Control Board
CGH	Compressed Hydrogen Gas
DEA	Diethanolamine
DAC	Direct Air Capture
EAF	Electric Arc Furnace
EC	Environmental Clearance
ED	Electricity Duty
FCEV	Fuel Cell Electric Vehicle
FCC	Fluid Catalytic Cracker
FT-SPK	Fischer-Tropsch Synthetic Paraffinic Kerosene
e-SAF	electro Sustainable Aviation Fuel
GH2	Green Hydrogen
GA	Green Ammonia
GHG	Greenhouse Gas
HEFA	Hydro-processed Esters and Fatty Acids
H-DRI	Hydrogen- Direct Reduction of Iron
HVIC	Hydrogen Valley Innovation Cluster
HRS	Hydrogen Refueling Stations
ISO	International Organization for Standardization
LOHC	Liquid Organic Hydrogen Carriers
OISD	Oil Industry Safety Directorate
MoEFCC	Ministry of Environment, Forest and Climate Change
MoRTH	Ministry of Road Transport and Highways
MSRTC	Maharashtra State Road Transport Corporation
MMTPA	Million Metric Tonnes Per Annum
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association, U.S
NGHM	National Green Hydrogen Mission
PEM	Proton Exchange Membrane
PNG	Petroleum Nat
PNGRB	Petroleum and Natural Gas Regulatory Board
PSUs	Public Sector Units
RIPS	Rajasthan Investment Promotion Scheme
SIGHT	Strategic Interventions for Green Hydrogen Transition
SOE	Solid Oxide Electrolyzers
SCoEs	State Centres of Excellence
SPCBs	State Pollution Control Boards
TPA	Tonnes Per Annum

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